ABSTRACT

SCOTT DURBIN. Utilization of a Water Market to Optimize Water Acquisition in the Edwards Aquifer Region. (Under the direction of Gregory W. Characklis).

The Edwards Aquifer (EA) is the sole source of water for 2 million people in south central Texas and provides the habitat for several endangered species. Recently, environmental concerns over declining aquifer levels and springflows resulted in a mandated reduction in water use. This project seeks to provide a decision-making framework for municipalities that utilizes several types of market transfers to meet demand, while simultaneously improving the efficiency of regional water use. A hydrologic and economic simulation model is developed that predicts monthly probability distributions of aquifer levels, market demand, and supply. The benefits of new alternatives (spot leases and options) are assessed along with the existing market transfer types (permanent transfers and annual leases). The model evaluates hundreds of combinations of the four transfer types to find the "optimal" portfolio that minimizes water acquisition costs while providing a specified level of supply. Results indicate that spot leases and options lead to a substantial reduction in the average cost and quantity of water needed to meet demand. The use of options results in a much smaller standard deviation in costs than spot leases. Given the risk adverse behavior of most municipalities, the ability of options to reduce cost without increasing risk may make them the most practical market alternative. Because of the water (and cost) savings that result from improved allocation through water transfers, markets should be considered as a viable alternative to meet demand in the EA.

ACKNOWLEDGEMENTS

First, I would like to acknowledge the researchers whose earlier work on the economic and hydrologic implications of aquifer management plans in the Edwards Aquifer helped to motivate this project. The previous research was carried out primarily by professors and students from Texas A&M Univeristy, especially Bruce McCarl and Keith Keplinger.

After their work, it was the great insight of Dr. Greg Characklis to further explore the potential benefits of water marketing in this water scarce region. Much thanks goes out to Dr. Characklis for his guidance throughout the project, his support and belief in me, and his ability to find research dollars to fund my work. Also, I, along with the rest of the students in this department, truly appreciate Dr. Characklis' efforts to improve student - faculty relationships and strengthen the overall social atmosphere of the department. I feel lucky to have been the first graduate student to work under him here at UNC, and I hope the work contained herein is a positive reflection of his abilities as a teacher and scholar.

To Dr. Don Lauria, you have challenged me mentally and spiritually over the last two years. I cherish the chats that we have had. My only regret is that we did not have more time this past year to discuss philosophies and life in general. I admire you tremendously and sincerely hope that we stay in touch.

Thank you to Dr. Marc Serre for showing an interest in my work and serving on my committee. Your comments and suggestions have been helpful and insightful. I wish you all the best as you continue your young career at UNC.

To C.L. Lassiter and Jack Whaley, thanks for all your help. Whether it was about financial matters, classes, or administrative paperwork, I would have been lost if I could not come ask you questions.

To the basement crew, Liz and Kirschburger, Johnson & Johnson, Slim Shadi, and the rest of the ENVR students that are still around, enjoy the rest of your time at UNC. If you're ever in Boston, look me up, but I'll be back around this way before too long to hit Franklin Street one more time and throw some back with you guys.

To JG and my peeps in Cary and Chapel Hill, thanks for being there and always being willing to go out and for not asking me too much about what I do all day at school. Lastly, to Karen and my family, there's too much to thank you for, so just thanks for everything.

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1. INTRODUCTION

1.1 Motivation

Water scarcity in the United States was once considered to be an issue only in the arid western states. However, steadily increasing pumping rates combined with low rainfall in recent years have made water scarcity a pressing problem throughout the United States. Domestic water supply authorities are fundamentally concerned with the problem of reliability, providing for the water needs of their customers with a high degree of certainty (Moreau 1987). In the past, high reliability has typically been achieved by increasing the size of water supply projects. However, as the available ground and surface water sources continue to be depleted, the financial and environmental cost of developing new water sources is becoming increasingly high. As a substitute to seeking water elsewhere, which would be expensive and deplete other water supplies, one possible solution is to utilize a water market in which existing water rights can be traded at prices that reflect the value of the scarce commodity. Allowing water rights to be traded to the highest valued use has been shown to result in a lower cost of reliability leading to a more economically efficient allocation of water (Wilchfort and Lund 1997; McCarl, Dillon et al. 1999).

Environmental concerns over declining aquifer levels and spring flows in the Edwards Aquifer region have resulted in the first ever issuance of groundwater pumping permits in Texas. In order to reduce pumping and increase spring flows, the permitted amounts will be lower than historical water use. Many municipalities in the region, especially San Antonio, are completely dependent on the aquifer to meet their demand. Now, these cities must curtail demand or find alternative sources of water to prevent shortfall. This project utilizes the Edwards Aquifer market to examine the possibility of using contingent (options) and short-term (spot market leases) transfers along with the current market alternatives (permanent transfers and annual leases) to reduce the cost and quantity of water supply needed to meet demand at a high level of reliability.

1.2 Background

The Edwards Aquifer (EA) is located in south central Texas, stretching for 180 miles east to west. The EA exhibits rapid recharge with velocity measured at up to 145 miles per year (2,100 ft/day) (Jensen 1988). Its waters serve agricultural, municipal, industrial, recreational, and ecological purposes in the region. San Antonio, which obtains its entire municipal water supply from the Edwards Aquifer, is one of the largest cities in the world to rely solely on a single groundwater source (Pedersen 1997). Approximately 2 million people and a considerable amount of economic activity are dependent on the EA water supply (Keplinger 1998).

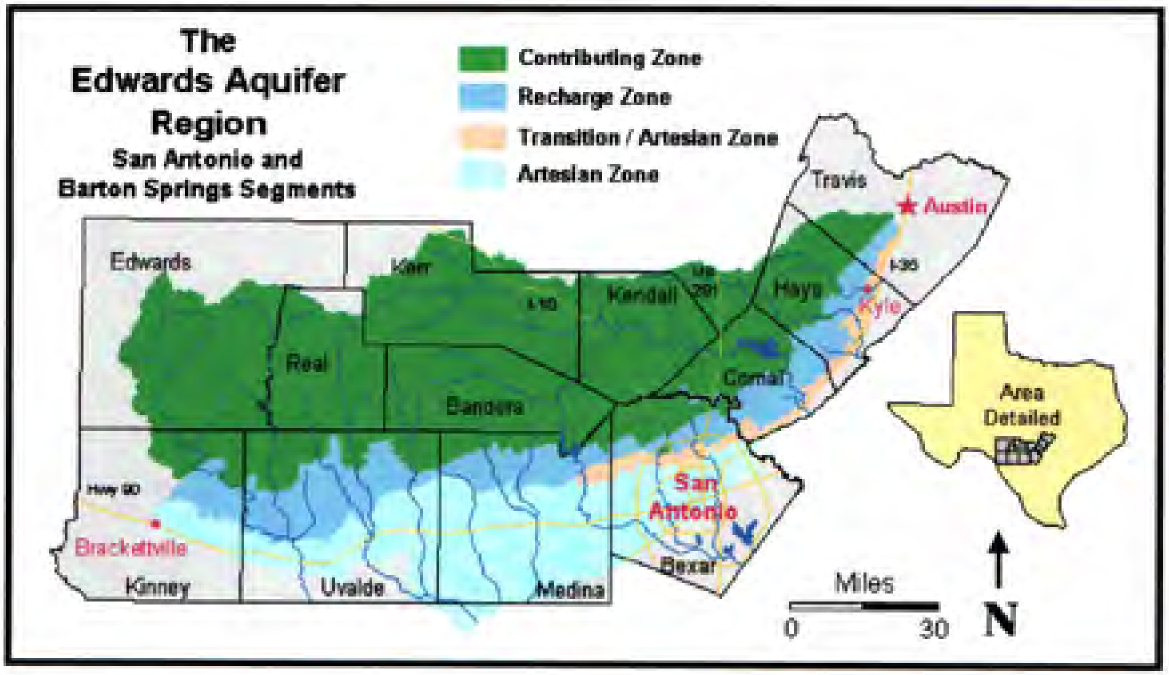

Figure 1.1: The Edwards Aquifer Region Located Near San Antonio, Texas

The San Antonio Water System (SAWS) provides water to over 1 million customers, comprising nearly 75% of all municipal EA water use. To the west of San Antonio, EA water is being pumped primarily for agricultural irrigation. About 80,000 acres of land are irrigated using water from the aquifer. To the east of the city, the EA feeds two artesian springs, the Comal and the San Marcos. These springs supply 30-70%

of the Guadalupe River flow each year and provide the habitat for five species listed by the US Fish and Wildlife Service (USFWS) as threatened or endangered (Keplinger 1998).

In the early 1990s, increases in pumping and a series of dry years resulted in the lowering of aquifer levels and a decline in spring flow at Comal and San Marcos. The reduction in spring flow negatively affected downstream users and angered environmental groups. The Sierra Club subsequently sued the state of Texas in a federal court claiming that allowing spring flows to decline constituted a "taking" of habitat under the Endangered Species Act (ESA). The district federal court upheld the ESA lawsuit and ordered that pumping limits be imposed to protect spring flow. As a result, a bill passed in the Texas legislature that led to several significant changes in the management of the Edwards. Namely, the bill:

- established the Edwards Aquifer Authority (EAA) and charged it with managing the aquifer.
- gave the EAA taxing and enforcement authority to collect fees, as well as define and monitor individual pumping rights
- required the EAA to allocate groundwater pumping rights amongst the approximately 1200 water users in the region. The EAA allocated rights based on proof of historical pumping amounts submitted by EA water users.
- created the institutional framework to market groundwater rights by making permits transferable (with some restrictions), and it set a cap on permits at 450,000 acre-feet (AF)[1] annually, to be reduced to 400,000 AF in 2008 (Eckhardt 2000).

Determining the allocation of pumping rights amongst all the users involved a long and contentious legal battle that finally came to a close in 2000 with the issuance of pumping permits. Individual permits specify an annual volume of pumping and may be

[1] An acre-foot is 325,850 gallons or about twice what the average household uses annually.

bought, sold or leased, all or in part, with minimal transaction costs. There are very few restrictions on where and how much can be sold as long as the buyer/seller are using the water within the EA. A user that wants to transfer water rights calls the EAA, the EAA posts a notice to sell, and the transfer process is normally approved quickly, with little required documentation. This relatively simple process helps to keep transaction costs low.

In all, the EAA issued 532,000 AF of permits of which 227,000 AF were assigned to municipalities, 247,000 AF to agricultural users, and 58,000 AF to industry. The allocation of these permits was done with the provision that the permits would quickly be reduced to 450,000 AF in the near future and to 400,000 AF by 2008.

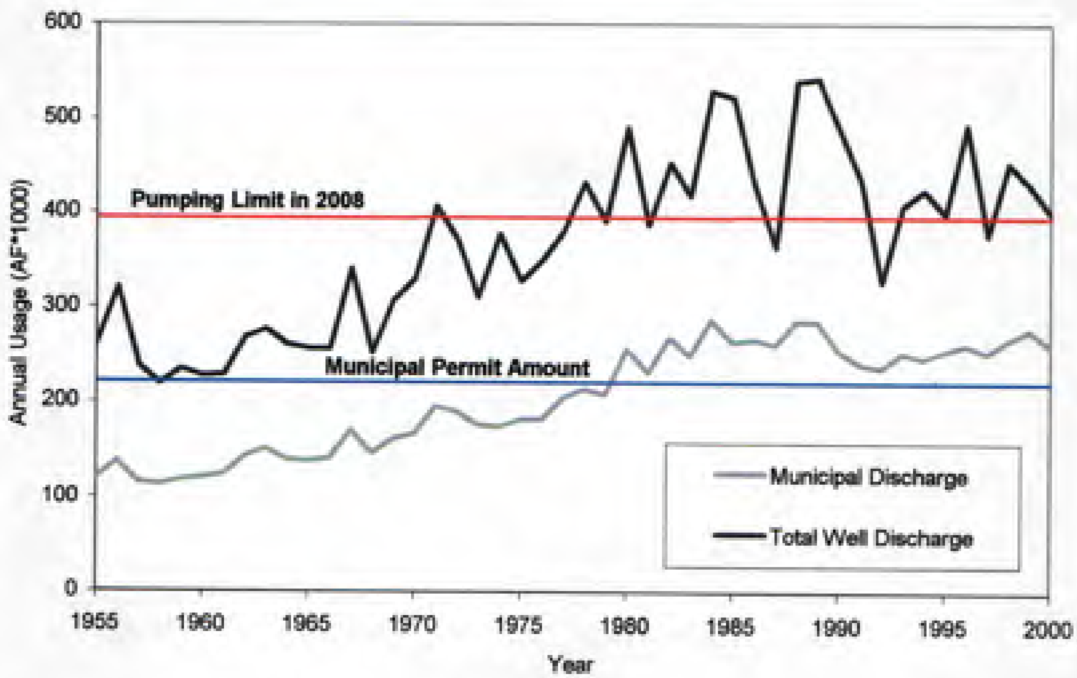

Figure 1.2: Annual Pumping in the Edwards Aquifer

As Figure 1.2 shows, municipal and total pumping from the Edwards Aquifer have increased steadily from the 1950's to the 1990's. For the last twenty years, the total well discharge has repeatedly surpassed the 400,000 AF limit that will go into affect in 2008. Similarly, since 1979, municipal pumping has exceeded the level at which they are now permitted to use. Average municipal water use is currently around 270,000 AF/yr or roughly 45,000 AF/yr above their current permitted amount.

The shortfall situation that the municipalities now face is further complicated by the drought management plan being developed by the EAA. In an attempt to increase spring flow during emergency situations, the proposed plan dictates that a municipality's pumping permits can be reduced under certain aquifer level conditions. A well in San Antonio, the J17 well, has been established as the indicator well for aquifer management (See Table 1.1).

Table 1.1: Well Level and Corresponding Cutbacks

	J17 Well Level (ft. above mean sea level)			
	Above 650	650-641	640-631	≤ 630
Percent Reduction In Monthly Permit	0%	5%	10%	15%

If in a given month, the water level in the well drops below 650 ft (above mean sea level), all water users in the San Antonio region must reduce their water usage by 5% for that month. For example, suppose SAWS' water rights are 120,000 AF/yr and they report to EAA that they use 10,000 AF a month. If the well drops below 650' in August, SAWS will only be able to pump 9,500 AF (a 5% reduction from the 10,000 AF monthly allotment) during that month. If the well drops below 640', the municipalities are cutback by an additional 5% for a total of a 10% reduction in their monthly permit. The municipalities are again cutback 5% for a total of 15% if the well falls below 630'. Thus, not only are the municipality's water rights less than they typically use, they are also dependent on how recharge and discharge affect the J17 well.

1.3 Water Supply Alternatives

In dry years, municipal demand will be higher than average, while at the same time, municipal permits are more likely to be reduced. This forces the municipalities to find even more water than their average 45,000 AF shortage. The alternatives for San

Antonio and the other municipalities to meet demand include using the water market to trade EA rights or buying the rights to ground and surface water sources outside of the region and then building transmission lines to bring in the water. Figure 1.3 shows the approximate annual lease price for EA water rights ($80/AF) compared to other alternatives that San Antonio is considering.

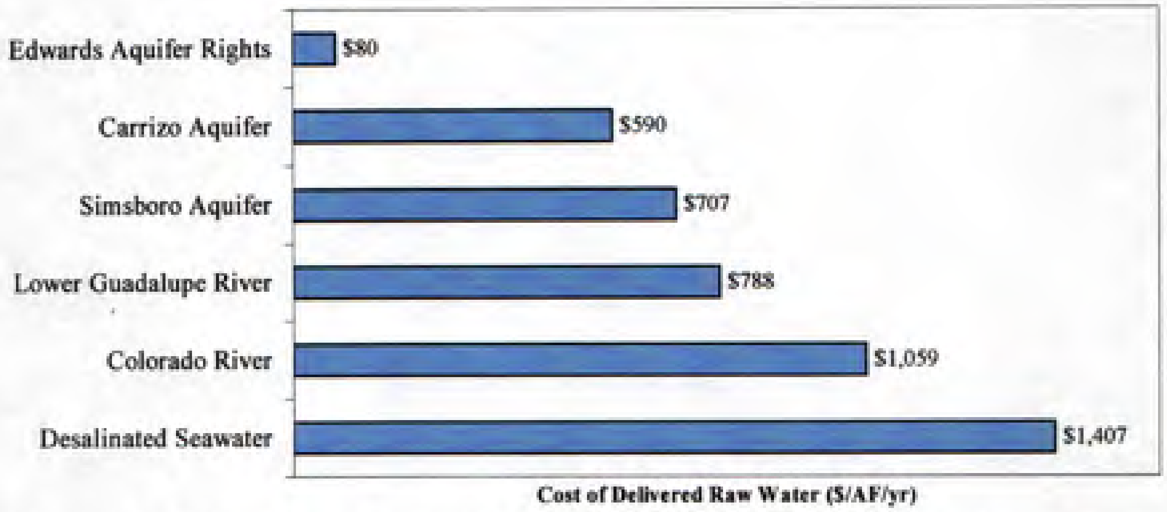

Figure 1.3: Prices of San Antonio's Water Source Alternatives (Edwardswater.com 2001)[2]

Although SAWS has acquired 50,000 AF of additional EA rights via the water market over the last two years, they eventually plan to utilize several of the sources listed in Figure 1.3. With the exception of the Carrizo Aquifer groundwater, which SAWS hopes to obtain by 2007, the structural solutions listed in Figure 1.3 are not planned to come on line until at least 2010. SAWS' goal is to have a 25% surplus during times of drought by 2010 (SAWS 2000). However, EA water rights are the only source in Figure 1.3 that can be used to meet SAWS immediate needs.

[2] Edwardswater.com compiled the information from working papers by the South Central Texas Regional Water Plan Group

Presently, SAWS is using the market to purchase rights in perpetuity or for multi-year leases. Buying rights and annual leases are allowed under current EA market rules, while options and spot leases are additional alternatives analyzed in this work to increase the liquidity[3] of the market. The four market alternatives being considered in this project are:

1) Buying Rights – this is a permanent transfer of water rights from agricultural users to a municipality.
2) Annual Leases- these occur on or just prior to January 1st. The municipality can use leased rights anytime during that calendar year. The ownership of the rights returns to the agricultural user for the next year.
3) Options - these are contingent transfers. The municipality pays a fee to an agricultural user early in the year for the right to lease their water later in the year at a set price. The municipality must decide later in the year (the exercise month) whether or not they need to lease the water (i.e.-exercise the options they bought). Exercised options can be used anytime between the exercise month and the end of the year.
4) Spot Market Leases- these can take place in any month and are used by the municipality to meet more immediate needs. The leases last from the time of transfer through the end of the year.

The variation in municipal demand (caused primarily by climatic factors such as temperature and rainfall), in conjunction with the potential permit cutbacks, makes municipal market demand highly uncertain. Monthly changes in demand and aquifer levels can result in sudden municipal shortages. By utilizing only multi-year purchasing alternatives, SAWS does not take advantage of the most current information regarding monthly demands and J17 well levels to anticipate and meet these shortfalls. Thus, with no method of adjusting to sudden shortages, they must plan for the worst-case scenario when purchasing rights and multi-year transfers. This results in more water rights sitting idle during non-dry years and leads to a net economic loss in the region (McCarl, Dillon

[3] A liquid market is one in which an asset can be bought or sold quickly with minimal transaction costs

et al. 1999). If contingent (options) or short-term (spot market leases) transfers were available on the market, municipalities would be able to use more current information regarding demands and aquifer levels to make decisions. Because the vast majority of cutbacks and shortfalls happen in the summer months, by delaying market decisions until later in the year, the municipality will have an improved estimate of their potential shortages. Consequently, they should have a better idea of the amount of water needed to achieve a certain level of reliability. The hypothesis investigated in this report is that by making the EA market more liquid, the municipalities will be able to more efficiently utilize the much cheaper alternative of EA water rights while simultaneously reducing the quantity of water that they need to meet a desired level of reliability.

Spot market leases allow the municipality to wait until a shortfall is imminent before they make a decision about how much water to buy. However, there is a tradeoff. From economic theory of supply and demand, one would expect the price of water to rise in dry months when demand increases and supply decreases. Therefore, it may be desirable to purchase a certain amount of rights, leases, and options at the outset of the year, instead of waiting until the month of a shortfall. This project seeks to explore the use of multiple water market transfer types in order to build a water asset portfolio of purchased rights, annual leases, options, and spot market leases that will maintain a desired level of reliability while minimizing cost. In order to find the minimum cost portfolio, Monte Carlo simulation is utilized to model the economic and hydrologic activity in the EA. A flow chart of the simulation process is depicted in Figure 1.4.

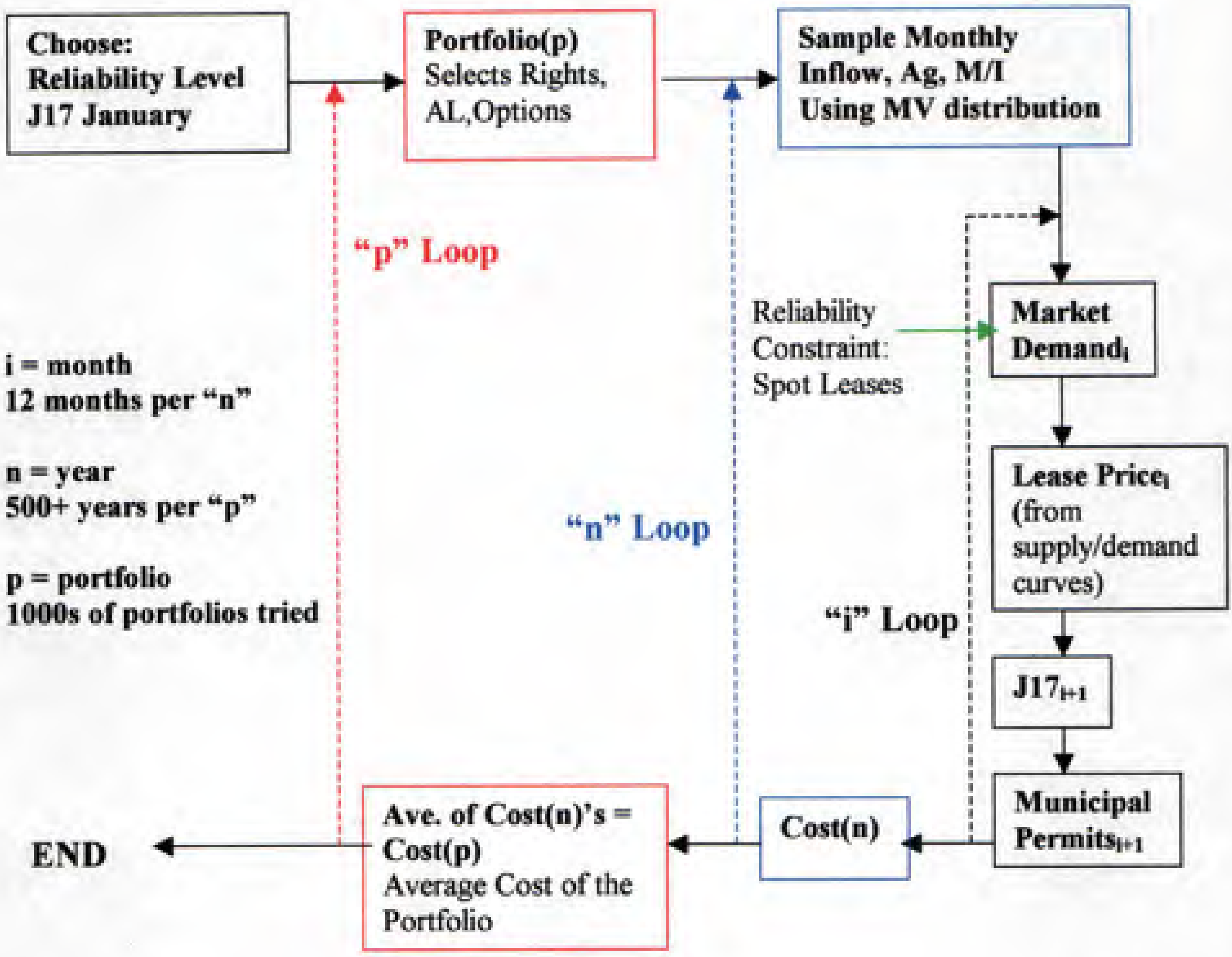

Figure 1.4: Flow Chart of Simulation Process

After selecting the starting January J17 well level and desired level of reliability, the model automatically selects a portfolio from a list of candidates. A portfolio consists of a certain number of rights, annual leases, and options. Spot leases are used as a slack variable to meet the monthly reliability constraint. Each portfolio is run through 500+ recharge and discharge scenarios (shown by the "n" loop in Figure 1.4). In each run, the number of exercised options and spot leases varies to meet the reliability constraint. At the end of the program run, we have a list of portfolios with their corresponding average cost of meeting demand. From this we can find the minimum cost portfolio for the selected reliability level and starting well height.

The simulation model improves the municipalities' knowledge of shortfalls by modeling the J17 well level to predict cutbacks and by using annual leases, options, and spot leases to delay purchasing decisions. The hypothesis herein is that the use of this market portfolio approach should reduce the quantity and cost of water needed to meet demand reliability, while also improving the regional efficiency of EA water use.

2. LITERATURE REVIEW

2.1 The Edwards Aquifer

The Edwards (Balcones Fault Zone, or BFZ) aquifer forms a belt 5 to 30 miles wide stretching 180 miles east to west across south central Texas. The Edwards (BFZ) consists of a confined layer of limestone fractured by a series of parallel faults, the largest of which is the Balcones Escarpment. Faults at the boundaries of the Edwards (BFZ) form groundwater divides that separate it from the Edwards-Trinity (Plateau) and Edwards-Trinity (High Plains) aquifers. The Edwards Aquifer was the first to be designated a Sole Source Aquifer in 1975 (Eckhardt 2000). An aquifer can be named a Sole Source Aquifer by the Administrator of the Environmental Protection Agency if the aquifer supplies 50% or more of the drinking water for an area and there are no reasonably available alternative sources should the aquifer become contaminated. Nearly 2 million people are dependent on the aquifer to serve their water needs.

2.1.1 Recharge

Establishing the relationship between recharge and aquifer storage is critical to predicting the J17 well level and the consequent permit restrictions. This section provides background on historic recharge in the EA as well as the hydrogeologic characteristics that affect aquifer storage.

The Edwards Aquifer is composed primarily of limestone formed during the early Cretaceous Period (Pedersen 1997) that ranges in thickness from 200 to 600 feet. The Glen Rose formation, which lies beneath the Edwards, is relatively impermeable and does not transmit water easily (Eckhardt 2000). Millions of years ago when the sea receded, the Edwards limestone was exposed to air and elements, and erosion took place. After the limestone was extensively eroded, other sediments were laid down on top of it to form a confining unit called the Del Rio Clay. The Edwards limestone extends to the land surface in the recharge zone (See Figure 1.1) and then dips underground where it is confined by the overlying clay layer (Pedersen 1997) and flows under artesian conditions.

As more layers formed above the Edwards limestone, the tremendous weight of the millions of tons of deposited sediment caused a series of parallel faults to form between the Edwards Plateau (just northwest of the aquifer) and the Gulf (Eckhardt 2000). Recharge occurs primarily from the downward percolation of streams through the crevices, faults, and sink holes located in the Edwards Plateau (Pedersen 1997).The highly fractured limestone has created conduits capable of rapidly transmitting large amount of water. The cross section of the aquifer in Figure 2.1 displays the fractured formation throughout the BFZ.

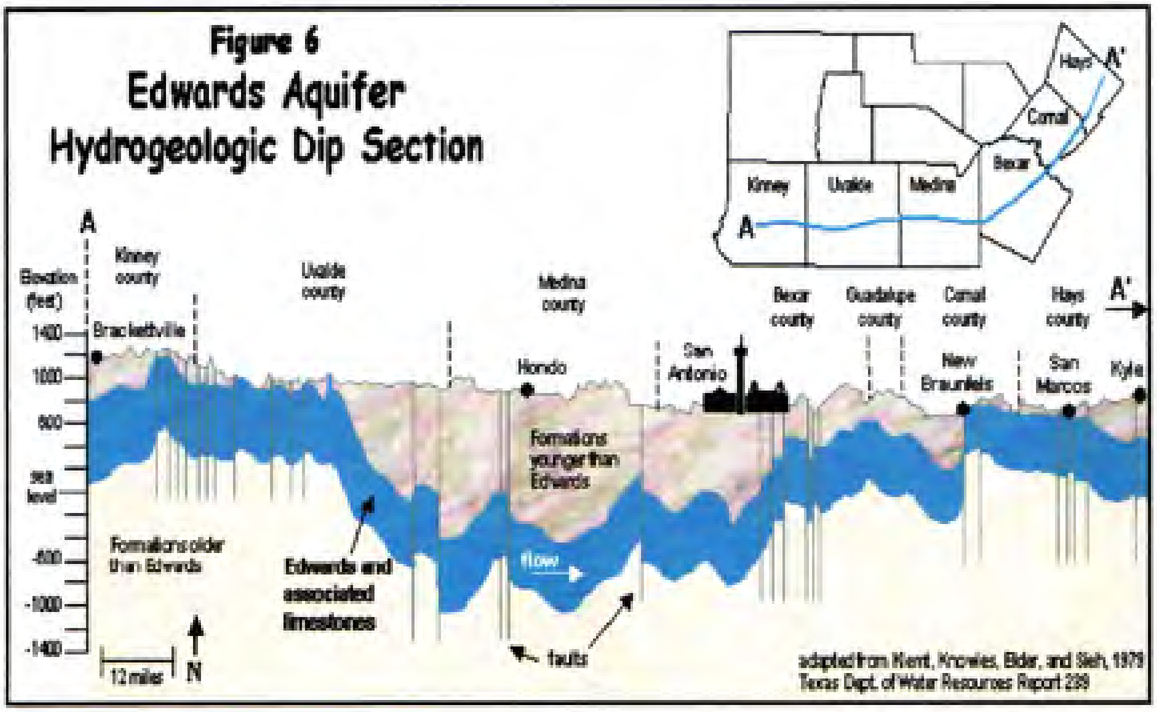

Figure 2.1: Cross-Section of the Edwards Aquifer(Eckhardt 2000)

Due to its highly permeable structure in the freshwater zone, the Edwards aquifer responds quickly to discharge and recharge. This is evident by the rapid fluctuations in the J17 indicator well during relatively short periods of time. For example, on six different occasions from 1980-1999, the J17 well height changed by more than 20 feet in a 30-day span. Because of its rapid, channelized flow, the Edwards Aquifer was designated an underground river by the Texas Water Commission in 1992. However, discontinuities in the permeable strata can inhibit or redirect the aquifer flow, making flow patterns complex. The Knippa Gap, located to the west of San Antonio, does not allow large amounts of water to pass quickly through it. As a result, water levels to the west of the gap display much less variability than wells to the east (Eckhardt 2000). Figure 2.2 displays how the flow pattern in Uvalde and Medina counties is altered due to the gap.

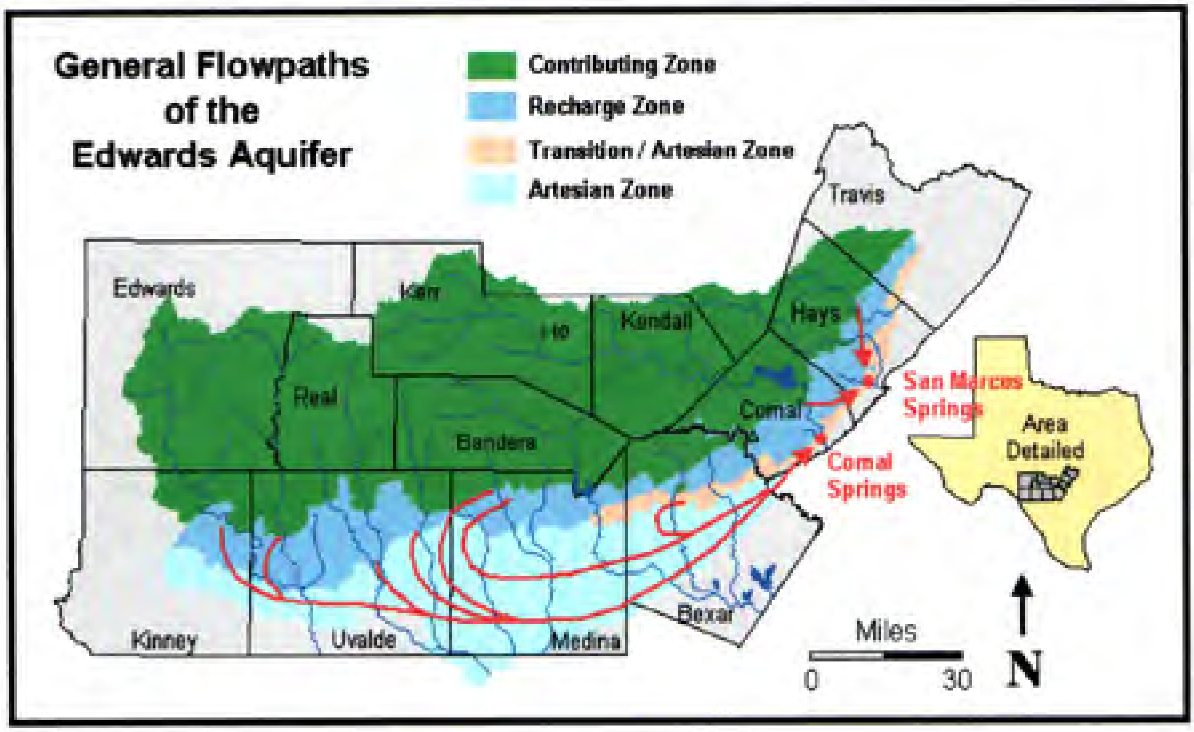

Figure 2.2: Edwards Aquifer Flow Paths (Eckhardt 2000)

The fault formation of the Edwards forces the water in Medina county to first flow southwest before heading northeast toward San Antonio (located in the center of Bexar County). After flowing through Bexar County, the aquifer discharges at springs, such as the Comal and San Marcos.

The first comprehensive report to estimate Edwards recharge was written by Puentes (1978) for the United States Geological Survey (USGS). USGS makes monthly recharge estimates using data from a network of streamflow and rainfall gauging stations (operated by USGS and the National Oceanic and Atmospheric Assocation) on the assumption that gaged areas relate to ungaged areas (Puentes 1978). USGS divides the recharge and contributing zones in Figure 2.2 into eight watershed basins that are separated by ground and surface water divides (See Figure 2.3).

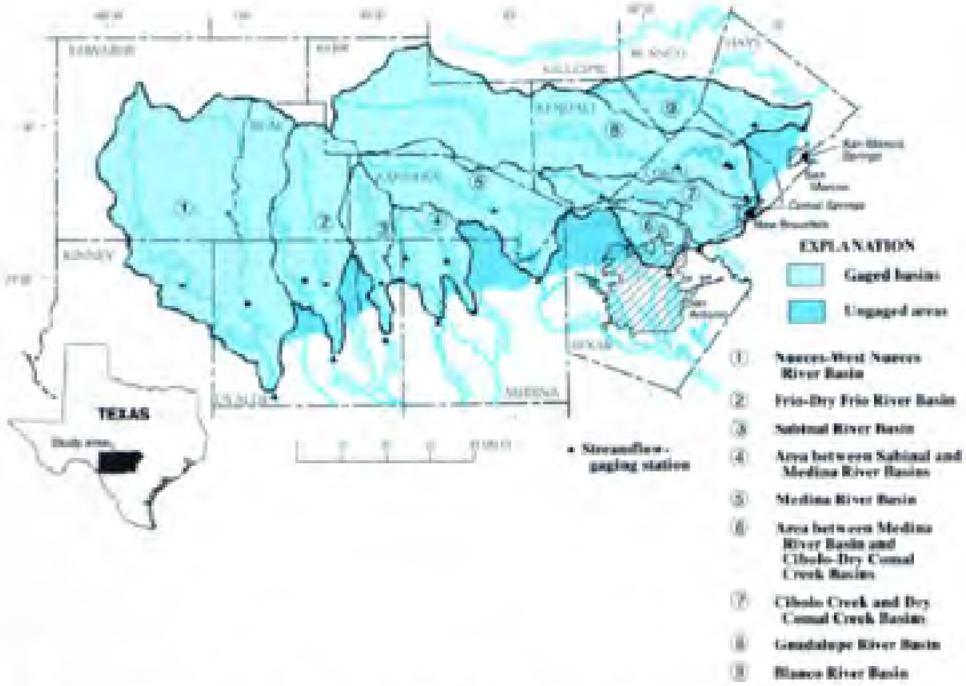

Figure 2.3: Recharge Basins for the Edwards Aquifer (Slattery and Thomas 2000)

USGS has slightly modified the watershed areas used to estimate recharge from the areas described by Puentes (1978). Recharge in the Guadalupe River Basin is no longer included in the recharge estimate because its contribution is negligible (Puentes 1978). Since 1932, the annual estimate of recharge has ranged from 43,700 AF in 1956 to 2,486,000 AF in 1992, with an average of 679,000 AF.

2.1.2. Discharge

Understanding the discharge quantities and locations in the EA is essential to modeling the aquifer and simulating market demand. Water is discharged from the aquifer from springs, agricultural pumping (primarily in the western part of the aquifer), and municipal and industrial pumping (primarily in the eastern part of the aquifer). The steady increase in municipal pumping (See Figure 2.4) has led to a reduction in spring flows during dry years. In November 2000, after months of deliberation and legal battles, the EAA issued pumping permits to all EA water users that totaled 532,000 AF. The EAA plans to buyout a number of users (mainly agricultural users) in the near future in order to reduce the permit total to the legislated limit of 400,000 AF (Eckhardt 2000). While municipal use has nearly doubled since 1955, agricultural use has fluctuated with no clear trend of increasing or decreasing usage (Figure 2.4).

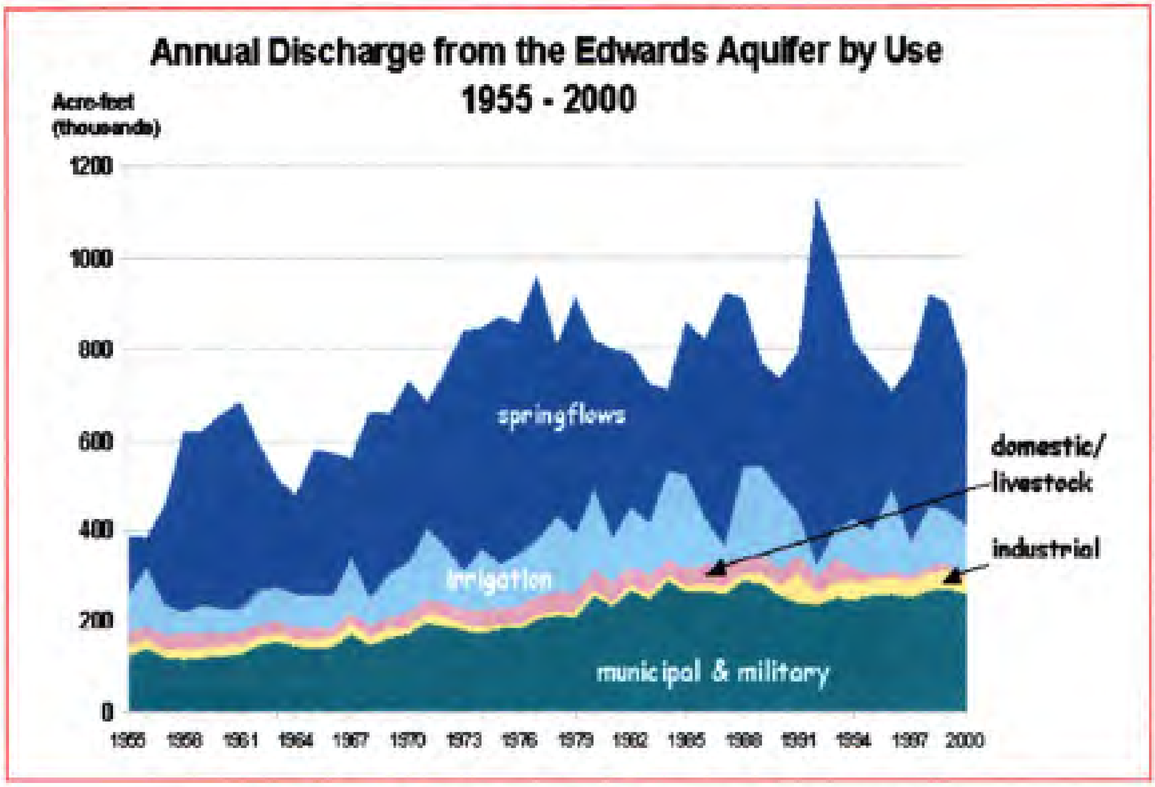

Figure 2.4: Discharge from the Edwards (Eckhardt 2000)

2.2 Indicator (J17) Well Level

Because the region's economic and environmental health are dependent on the aquifer, modeling of the Edwards Aquifer has taken place for over thirty years. The gradual development and improvement of these models will assist in creating an aquifer model for this project that predicts the J17 indicator well level in each month.

In the mid-70's, the Texas Water Development Board (TWDB) developed the first finite-difference model of the Edwards Aquifer. The model investigated the influence of projected water demands on aquifer storage and spring flow to discover whether groundwater management could protect spring flow at Comal and San Marcos Springs (Eckhardt 2000). The model concluded that the aquifer could indeed meet the demand projections, but that the flow at the San Marcos and Comal Springs would cease by 2020 (Klemt 1979). It also suggested that the drought-flood sequence of the 1950's (worst on record) had less affect on the springs than the long- term affect of increased pumping by humans. The report concluded that with proper groundwater management, the flows at the San Marcos and Comal Springs could be maintained.

In the early 1990's, two geologists from the TWDB, David Thorkildsen and Paul D. McElhaney, utilized new information regarding reduced pumping, aquifer management, and aquifer flow characteristics to refine the earlier TWDB model. By this time, one of the aquifer management ideas being discussed was the "dry-year option", under which pumping would be restricted based on the level of the J17 monitoring well. Thorkildsen and McElhaney's model converted the annual estimates of pumping and recharge from the earlier model into monthly simulations of the J17 level and the San Marcos and Comal springflows. They utilized hypothetical pumping restrictions based on the simulated J17 levels and determined the affect on the aquifer and springs. The model concluded that large reductions in pumping in the San Antonio region would be necessary to keep the San Marcos and Comal flowing at a minimum level (Thorkildsen and McElhaney 1992).

In 1993, Bruce McCarl and Lonnie Jones of the Texas A & M University Agricultural Economics Department worked with graduate students R. Lynn Williams and Carl Dillon to investigate the implications of management plans that were being proposed for the aquifer at the time. Over the next seven years, McCarl worked with a number of students to determine the hydrologic and economic impact that various aquifer management plans would have on the regional economy. McCarl's models split pumping into agricultural, municipal, and industrial sectors, and simulated the affect of various recharge and discharge scenarios on the J17 well levels and springflows. The models used the most recent suggestions of J17 elevation-triggered pumping limits to restrict pumping in certain sectors and optimized water allocations among the various sectors of users based on maximizing economic welfare. It also suggested that the proposed pumping limits would require the creation of pumping rights and a water market to maintain economic efficiency (McCarl, Dillon et al. 1999).

McCarl et al.'s model estimated the coefficient of municipal pumping, agricultural pumping, and recharge on J17 levels. The results indicate that agricultural pumping has a 7 times greater effect on the springflow than municipal pumping (Keplinger, McCarl, et al. 1998). This is due to the location of the Knippa Gap and the direction of the flow paths depicted in Figure 2.2. Using a simple OLS regression analysis, the model estimated the coefficients on the independent variables using simulated and historic data (See Table 2.1).

Table 2.1: Results of OLS Regression on Ending J17 Well Levels (Keplinger and McCarl 1995)

		Starting Head Level			Pumping			
		J17	Sabinal	Recharge	Agricultural	Municipal	Intercept	R-Square
J17 Ending Elevation	Historic Data	0.26	0.12	0.00002*	0.000036*	-0.000103*	671.8925*	0.7625
	(t-stats)	(1.03)	(1.08)	(7.14)	(0.91)	(-2.85)	(589.88)	
	Simulated Data	0.292*	0.152*	0.000013*	-0.000032*	-0.000111*	656.1232*	0.9089
	(t-stats)	(29.16)	(20.46)	(46.53)	(-20.00)	(-109.38)	(5332.99)	

* Indicates that the variable was significant at the 10% level

The high R^2 values for these regression analyses supported the theory that a relatively simple model would suffice in modeling the aquifer. Table 2.1 also shows that recharge, agricultural pumping, municipal pumping, the J17 starting head level, and the Sabinal well starting elevation are significant factors in the ending J17 well level. This data provides a model framework, as well as coefficients, that will assist in developing the J17 model for this project.

2.3 Water Demand

In order to predict the potential advantages and disadvantages of relying on a fully functioning water market to meet EA municipal demand, the prices for the market alternatives must be established. Prices will depend on economic theory of supply and demand. The quantity of water demanded by the agricultural and municipal users will vary inversely with the price of the water. In order to estimate the agricultural and municipal demand curves, we must determine the value of water in each sector as well as their price elasticity of demand. Once the demand curves are known, one can begin to determine how much water will be bought, sold, or consumed at various market prices. (Explanations of the Cobb-Douglas demand function and the price elasticity of demand are located in Appendix E). The following two sections look at how previous studies have estimated agricultural and municipal demand curves.

2.3.1 Agricultural Demand

Studies of the United States' agricultural water demand have existed for nearly half a century. The interest in agricultural water demand stems mainly from the arid western United States, where over 80% of consumptive water use is attributable to agriculture (USGS 1993).

The most direct approach to estimating the agricultural demand function is to observe a competitive market in which farmers buy and sell water rights (Diaz, Brown et al. 2000). Some water markets exist in the western U.S., eg.-the Edwards Aquifer, in which agricultural users sell water to municipal or industrial users. However, these markets are rarely the type of open, competitive market that enables the agricultural elasticity of demand to be estimated (Diaz, Brown et al. 2000). As a result, deriving the agricultural demand functions typically involves treating irrigation water as an input to the agricultural production function. By establishing the relationship between irrigated land and crop output (prices and quantities), one can derive the value of irrigation water.

Initial studies of agricultural demand focused on comparing crop yield and soil moisture content. However, the increasing availability of crop budgets beginning in the 1970s would replace the use of the plant growth versus soil moisture relationship for deriving values of irrigation water. Crop budgets describe the per acre cost of growing a particular crop. The crop yield and price information are used to estimate the farmer's gross income. Subtracting the fixed and variable costs from this income leaves the net value of returns per acre. The maximum cost that farmers could pay for irrigation water is then estimated as the final net return minus the opportunity cost of the farmer's time. This information can be combined with linear programming (LP) techniques to describe the water demand function.

The LP models use buying irrigation water as one activity in the model. The price of irrigation water is varied across the possible spectrum of values and the model is solved at each price. Following the principles of economic efficiency, irrigation water is applied until the marginal cost of water equals its marginal benefit (crop yield per unit of water x crop price) (Kindler 1988). In this manner, an optimal amount of irrigated water is calculated for each farm at each water price based on the farm's crop mix. The fixed costs of production do not affect the optimum irrigation water application once the crop is planted, but they will affect the decision to plant in the first place. Fixed costs can lead to a choke price, above which no crops are grown. The resulting demand function from an LP model is often stepped and convex to the origin, with each step representing a different crop or the same crop in a different climatic or geologic setting (Diaz, Brown et al. 2000). From the stepped functions, the demand function shape and elasticity can be estimated.

In the early 1990's, a stochastic, dynamic LP model was developed for the EA using the agricultural component of the aquifer model developed by McCarl et al. (1993). This regional agricultural model attempted to predict the acreage of land that would switch from irrigated agriculture to dry land farming given different per-acre compensation levels. Activity in six counties in the Edwards was modeled under nine recharge/weather states of nature with unequal probabilities. The model takes into account each farm's crop mix, irrigation strategy, and pumping lift cost (Keplinger et al. 1998). Data describing yields and water use were developed using the Erosion Productivity Impact Calculator (EPIC) crop growth model(McCarl, Dillon et al. 1993). The EPIC results were integrated with crop budget and pumping cost data to decide on crop mix, land allocation between irrigated and dry land production, and furrow/sprinkler choice.

The model assumes that a farmer would switch to dry land farming if the compensation level offered plus his/her profit from dry land farming would exceed the profit he/she could receive from irrigated farming. The payments offered farmers are called irrigation suspension payments, modeled after the irrigation suspension program (ISP) implemented in the EA in 1997. The model simulated the responses to alternative payment levels for three different ISP scenarios. The first ISP scenario pays farmers to suspend irrigation in January, while the other two wait until June to pay farmers to stop irrigating. Of the two June ISPs, one scenario assumes that the farmers have knowledge of the impending ISP and can adjust their crop mix accordingly, while in the other scenario, no prior knowledge of the ISP is given. The results indicate that the eastern counties are more willing to sell than the western counties (Keplinger 1998). The January 1st cutoff significantly reduces irrigation water demand by selling to municipalities and converting to dry land farming. However, the June 1st anticipated and unanticipated scenarios result in a much more inelastic demand curve than the January cutoffs. The curves generated by the EDSIM program are estimates of the annual agricultural demand curve in January and in June. Estimating the agricultural price elasticity of demand from the ISP curves will be described in the Methodology section

Although agricultural elasticity can be estimated from McCarl et al.'s work, comparison with agricultural elasticities found in previous studies would help confirm the validity of those estimates. As evident from the LP models described above, agricultural elasticity is a function of crop type and climate, and therefore regionally dependent. There are only a few studies of agricultural elasticity in Texas. A study by Characklis et al. (1999) found the elasticity of field crops in the Lower Rio Grande region of Texas to be –0.7 based on the Cobb-Douglas functional form. A study in the High Plains region of Texas, also using the Cobb-Douglas function, found the irrigation water price elasticity to be –0.8 (Nieswiadomy 1985). All of this information will be considered when deriving the agricultural demand curves used in the market simulations.

2.3.2 Municipal Demand

A rapidly growing number of papers related to municipal water demand have become available in the latter 80s and 90s. This is due primarily to the increasing interest of municipalities to: 1) encourage conservation through demand management and 2) understand the seasonality of water demand. Several studies (Nieswiadomy 1992; Epsey, Epsey et al. 1997; Michelesen, McGuckin et al. 1999) have looked at the determinants of residential water demand and attempted to quantify the effects of these determinants using a regression analysis. With water consumption per household as the dependent variable, these regression analyses typically involve factors such as income rainfall, temperature, persons per household, and average or marginal price.

In these analyses, marginal and/or average price is used as an explanatory variable. Statistically, studies have shown that customers respond more to average rather than marginal prices of water (Griffin and Chang 1989; Griffin and Chang 1991; Nieswiadomy 1992). A study of urban water demand in the United States using the most current American Water Works Association [1984] survey of 430 U.S. utilities found price elasticity to range from -0.29 to –0.45 (Nieswiadomy 1992). Griffin and Chang's (1989) study of community water demand in Texas estimated elasticity using four different functional forms. The average monthly elasticity for the models ranged from –0.27 to –0.33, with elasticity in the summer months being slightly higher than in the winter. Along with the season, pricing structure has also been found to signficantly influence the estimate of residential price elasticity (Epsey, Epsey et al. 1997). The average residential price elasticities of demand calculated in regions comparable to the EA are presented in Table 2.2.

Table 2.2: Municipal Price Elasticities of Demand

Source	Model	Price elasticity
Griffin & Chang (1989)	Cobb-Douglas	-0.35 (Texas)
Nieswiadomy (1992)	Cobb-Douglas	-0.45 (West)
Michelson et al. (1999)	Cobb-Douglas	-0.23 (SW region)

Results from the municipal studies on price elasticity indicate that elasticity is typically in the range of –0.25 to –0.50 (Epsey, Epsey et al. 1997). At first glance, it might appear that this range is not that different from the agricultural elasticities mentioned in the previous section. However, it is important to keep in mind that municipal price elasticity of demand refers to the treated water delivered to the tap, while agricultural elasticity refers to the untreated water pumped out of the ground. Therefore, the unit cost of municipal water is approximately an order of magnitude larger than the unit cost of agricultural water. So, if the cost of raw water increases due to market activity, the percentage change in price will be much larger for the agricultural users than the municipal users. Consequently, even if the agricultural and municipal elasticities were the same, the actual decrease in demand would be far greater in the agricultural sector than in the municipal sector.

2.4 Water Marketing

Recent years have seen water scarcity become a reality in the United States. As a result, both the Bureau of Reclamation and the US Army Corps of Engineers are focusing on improved management of resources rather than developing new supply projects (Jordan 1999). Therefore, a growing number of regions are utilizing water markets as a way to more efficiently allocate water.

In order to have an effective system of marketing water, 5 prerequisites are necessary (Jordan 1999):

1) Water rights must be clearly established
2) The water right must be quantifiable
3) An enforceable institutional system must be in place to enable transfers to be done without overly burdensome transaction costs
4) Infrastructure or method to transfer water must exist
5) Externality issues must be taken into account

The EAA was formed in order to regulate water usage in the Edwards and to promote a water market (Keplinger and McCarl 2000). When the EAA issued permits in 2000, the foundation for a water market was fully established. During the past decade, several researchers have studied the potential advantages and disadvantages of utilizing water markets in the Edwards and other western states to more efficiently allocate water.

2.4.1 Marketing Possibilities in the EA

A study performed in 1999 by Watkins and McKinney developed a screening model to support the selection of alternatives for meeting future water demands and protecting sensitive ecosystems in the Edwards. Although the use of an active market was not considered, they did include dry-year options as one proposed alternative to demand management. The dry-year options under consideration in their study involve paying farmers to not irrigate their land when water levels drop below a pre-determined trigger level. This is considerably different than the options being considered in our project. Their results indicate that, under current demand levels and average rainfall conditions, the combination of water conservation, reuse, and dry-year options is "a good solution to the San Antonio region's water resources problem". Further, they suggest a plan that is multifaceted in order to provide more flexibility to deal with the uncertainty of hydrologic conditions. Their fear is that if the region plans for a drought by investing in large supply projects, and then a drought does not occur, it will appear that huge sums of money have been squandered. Conversely, if planning is done for expected conditions, there is risk of severe environmental and economic hardship in time of drought. Watkins and McKinney's concluding comment is that clearly some form of hedging is needed to minimize the chances of either regrettable outcome which could erode stakeholder confidence and impede regional solutions to water problems in the future. A market that includes options or spot market leases is one way for municipalities to "hedge" their bets in the way that Watkins and McKinney suggest.

Although the Edwards market does not utilize options or spot-market leases, the use of dry-year options during periods of drought has been proposed since the early 90's. In 1997 the EAA instituted a fallowing plan called the pilot Irrigation Suspension Program (ISP) in which local farmers were paid to not irrigate for the 1997 cropping season. Farmers offered prices for fallowing their land, and the EAA chose whether or not to accept the bids. The average of the accepted bid prices was approximately \$100/AF. Keplinger and McCarl (2000) determined this price to be artificially high with the true value of irrigation water closer to \$35/AF. An ex-ante evaluation of the ISP showed that a market in the Edwards aquifer region was feasible (Keplinger and McCarl 2000) and concluded that the creation of water rights that could be sold, leased, or optioned would improve economic efficiency.

To assess the economic impact of various drought management plans, the aquifer model described earlier (Klemt et. al 1979, Thorkildsen and McElhaney 1992) was adapted to assess the affect of water transfers in the EA. Through the work of McCarl et al.(1993), Williams (1996), and Keplinger et al (1996), an economic and hydrologic aquifer simulation model (EDSIM) was developed in which water was allocated to the highest and best use in terms of generating net economic value (McCarl, Dillon et al. 1999). The model was run under various pumping and springflow constraints with the results simulating the "best" regional economic outcome. In effect, EDSIM simulates water use in an idealized market with no transaction costs. McCarl and Dillon et al. (1999) considered two market forms: temporary (annual lease) and permanent (sale) markets and examined the potential trades between agricultural and non-agricultural interests under the 400,000 AF limit. In the absence of a water market, the marginal use value is about \$70/AF lower for the agricultural than nonagricultural users. If permanent transfers are allowed, the difference reduces to about \$4/AF. By allowing leasing (with no guaranteed base level of water for the farmers) the marginal use value for both sectors would be equal. By not allowing transfers, it is estimated that the 400,000 AF limit reduces regional pumping user welfare by \$1.1 million/yr. It is also estimated that by diverting agricultural water to nonagricultural use under drought conditions regional welfare could increase by more than \$2 million/yr.

Currently, permanent transfers and multi-year leases are the only market alternatives utilized in the Edwards. The results of the studies on marketing in the EA suggest that the use of a market that includes options and spot market leases may reduce municipal supply costs and provide a net economic benefit to the region. However, further review of studies in other regions that involve a more in depth evaluation of options and water supply optimization would be beneficial in formulating a plan to improve marketing and allocation in the EA.

2.4.2 Water Markets Outside the EA

Utilizing a case study in northeast Colorado, Michelsen and Young (1993) evaluated the viability of using option contracts to temporarily transfer irrigation water rights to nonagricultural users during times of droughts. They simulated the hydrologic, institutional, and economic relationships in the region and compared the benefits of purchasing option contracts versus buying water rights. Michelsen and Young (1993) used a linear program similar to the EDSIM model to evaluate the exercise cost. They defined exercise cost as the "minimum amount that must be paid to a farmer to maintain the same level of net income in the event of option exercise". This cost varies from site to site based on crop mix and from year to year based on rainfall conditions. The exercise costs ranged from $39/AF to $135/AF with an average of $85/AF. Results indicate that the net benefits of options depend on such factors as water right price appreciation, discount rates, option prices, exercise cost, and frequency of exercise. The study concludes that, under a wide range of economic conditions, options have the potential to provide secure urban drought water supplies at a lower cost than water right purchases while still maintaining the agricultural base (Michelsen and Young 1993).

Michelsen and Young's conclusions encourage the inclusion of options in a market that allows only permanent transfers. However, their method of using and valuing options is significantly different than what could be done on a fully functioning water market. For example, the options contracts proposed by Michelsen and Young are not short-term alternatives (contracts are for 20 years) and can be exercised numerous times over the extent of the contract (rather than having a single exercise decision, as is typical with options). Further, no spot market existed in the area, so the decision to exercise the options was solely dependent on the supply conditions rather than market price. Because there was no spot market, the option valuation did not incorporate market activity or water price volatility as would normally be done when pricing a contingent transfer. If spot market leasing was considered as a market alternative along with buying rights and options, the option contracts could be more accurately valued and their benefits more precisely assessed.

Spot market leases were incorporated into Lund and Isreal's (1995) least-cost optimization model. The model also included dry-year options, water conservation, and traditional water supplies water source alternatives. Their model is a two-stage linear program in which options are bought in the first stage, and conservation or spot leases are utilized in the second stage if demand surpasses supply. The results indicate that conservation and spot market leases are optimal for smaller shortfalls, and as the magnitude of the shortfall increases, the optimal number of option and spot lease purchases increase. In a follow up paper, Lund and Wilchfort (1997) find that by allowing more spot market and/or dry-year option transfers, urban water supply costs can be significantly reduced.

The results of the two-stage LP support the use of options as well as spot market leases to meet municipal demand at a lower cost. However, the model's results are largely dependent on the prices of the alternatives, and no explanations or justifications for the option and spot market prices used in the model are given. Also, the model is discrete; there are no uncertainties in market supply, demand, or price incorporated in the model. Therefore, it cannot compare the reliability of meeting demand versus the cost of the optimal scenario.

Models or simulations that analyze the feasibility of options and/or spot market transfers while incorporating pricing that directly reflects the stochastic supply and demand remain largely unexplored. In the program developed for the project explained herein, recharge, municipal demand, and agricultural demand are defined as probability distributions rather than discrete quantities. The results of this project address a range of potential market types, from a market that allows only permanent transfers to one that includes permanent transfers, annual leases, options, and spot market leases. The simulation results from each market type enable us to develop the relationship between the reliability of meeting demand versus the cost of the optimal portfolio. Also, a considerable effort is made to more rigorously value options than has been done previously. This is accomplished by utilizing option pricing theory in conjunction with simulated activity on a fully functioning EA water market. The background and evaluation of options is detailed in the following section.

2.5 Option Pricing

Although they are a common market alternative on stock exchanges, options have not been frequently used in water markets. Typically, the type of option seen in water markets, often referred to as a "dry-year option", is one in which a utility reserves the right to lease water from other users in times of drought. The price of a "dry-year option" is usually a pre-determined value that has little to do with lease price volatility or option pricing theory in general. However, in this project, a more rigorous valuation of options will be made, and options will be priced and traded in a manner similar to the way in which stock options are traded on security markets. In order to do this, we must establish the regulatory and pricing framework for trading and using options in the EA.

A derivative security is a security whose value depends on the values of other more basic underlying variables. A stock option is a derivative security whose value is contingent on the price of the stock (Hull 1993). Since the early 1970s, options trading has enjoyed an expansion unprecedented in American securities markets (Cox, Ross et al. 1979). The type of options utilized in the EA market simulations is a European call option. The purchase of a European call option in the EA gives its owner the right to lease a fixed number of water rights at a later date for a set price. The date specified in the option agreement is called the exercise (or expiration) date, and the set price is the exercise (or strike) price. At the time of the exercise date, if the value of the asset (water right lease price) is greater than the exercise price and the owner of the option needs water, then the option is exercised. If the opposite is true, then the option is not likely to be exercised and the purchaser of the option incurs a monetary loss equal to the amount spent to purchase the option. Typically, the option price is less than the exercise price. Therefore, an EA user that fears a potential shortfall can pay a smaller sum of money upfront (the option price) to assure themselves that they can obtain water later in the year (at the specified exercise price).

Before we can use options in the market, we must price them. There a five factors affecting option prices (Hull 1998):

1) Current stock price (in our case, the water lease price), S
2) Strike price, X

3) Time to expiration, T
4) Volatility of the stock price, σ
5) Risk-free interest rate, r

Some assumptions also must be made to derive option prices:

1) There are no transaction costs
2) No dividends are paid
3) Borrowing and lending are possible at the risk-free rate of interest
4) There are no arbitrage[4] opportunities

The option call price can be derived using risk-neutral valuation and the above assumptions. In a risk-neutral world, the expected return on the stock must be the risk-free rate of interest otherwise arbitragers would close the gap. A one-step binomial tree is a simple and useful technique to visualize this concept (See Figure 2.5). Consider a European call option that allows you to lease a water right for $51/AF next month. Suppose the current water lease price is $50/AF and in one month it will either move up to $52/AF or down to $48/AF[5] with probability p and p-1, respectively. We want to determine the value of the option contract, i.e.- the option price.

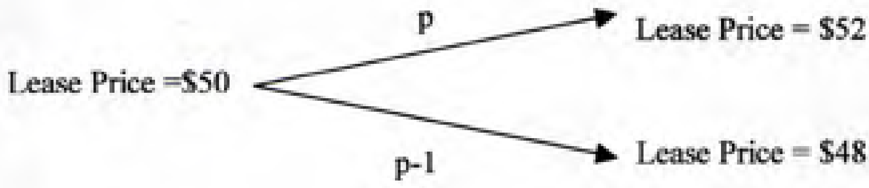

Figure 2.5: Lease Price Movements in a One Step Binomial Tree

[4] Arbitrage- trading strategy that involves taking advantage of the fact that two or more securities are mispriced relative to each other
[5] The remainder of the section on options is primarily an adaptation of excerpts found in Hull 1993 and Hull 1998.

Let the one-month risk-free rate of interest equal one percent. Then, based on the risk-neutral argument, the probability of an upward movement must satisfy:

$$\$52 * p + \$48 * (1 - p) = \$50 * 1.01 \qquad \text{Equation 2.3}$$

that is, p must be 0.625. The expected value of the call option in 1 month using this value of p is:

$$0.625 * (\$52 - \$51) + 0.375 * \$0 = \$0.625 \qquad \text{Equation 2.4}$$

This is the expected terminal value of the call option in a risk-neutral world. The present value of this expected value when discounted at the rate of interest is:

$$\frac{\$0.625}{1.01} = \$0.619 \qquad \text{Equation 2.5}$$

So, the option contract would have an option price of \$0.62/AF and a strike price of \$51/AF. In general terms, the expected value of a European call option at maturity in a risk-neutral world is

$$E[\max(S_T - X, 0)] \qquad \text{Equation 2.6}$$

where E denotes the expected value and S_T is the lease price in the expiration month, T. From the risk-neutral valuation argument the European call option price, c, is the value of this discounted at the risk-free rate of interest, that is:

$$c = e^{-r(T-t)} E[\max(S_T - X, 0)] \qquad \text{Equation 2.7}$$

In the early 1970s, Fisher Black and Myron Scholes presented the first completely satisfactory equilibrium option pricing model. Black and Scholes derived the Black-

Scholes option pricing formula by assuming that stock prices follow a random-walk process with a constant growth rate, μ, and volatility, σ. The random-walk assumption implies that the stock price at any future time has a log-normal distribution. The log-normal distribution means that the log of the variable is normally distributed. Thus, the log of the stock price, $\ln(S_T)$, at time, T, is normally distributed as shown below:

$$\ln S_T \sim \phi[\ln S + (r - \frac{\sigma^2}{2})(T-t), \sigma\sqrt{T-t}] \qquad \text{Equation 2.8}$$

Where, Φ indicates a normal distribution. The mean of the distribution is the first term in the brackets, $\ln S + (r - \frac{\sigma^2}{2})(T-t)$, and the second term, $\sigma\sqrt{T-t}$, is the standard deviation.

By putting this value for S_T into Equation 2.7 and solving using integral calculus, Black and Scholes developed the following result for non-dividend option pricing:

$$c = S * N(d_1) - Xe^{-r(T-t)}N(d_2) \qquad \text{Equation 2.9}$$

where,

$$d_1 = \frac{\ln(S/X) + (r + \sigma^2/2)(T-t)}{\sigma\sqrt{T-t}}$$

$$d_2 = d_1 - \sigma\sqrt{T-t}$$

and N(x) is the cumulative probability distribution function for a standardized normal variable.

One of the most difficult aspects of utilizing the Black-Scholes is estimating the volatility, σ. However, if, at the time of expiration, the expected lease price, S_T, can be estimated through other methods, then Equation 2.7 can be evaluated without having to integrate Equation 2.7. One such method involves utilizing Monte Carlo analysis. The water lease price in any month is dependent on several underlying variables, such as recharge, discharge, and previous market purchases. By replacing these variables with their probability distributions and running a Monte Carlo simulation, we can establish the distribution of the lease price, S_T, in the expiration month. With the lease price distribution known, we can calculate the max(S_T -X,0) for numerous possible values of S_T. Then, the expected value of max(S_T -X,0) can be estimated as the average of all of these values. Once this is known, the expected value is discounted at the risk-free rate of interest in accordance with Equation 2.7 (shown again below) to find the option price, c.

$$c = e^{-r(T-t)} E[\max(S_T - X,0)]$$

By using the actual lease price distribution, this method directly incorporates market activity and the volatility of the lease price into the value of the option. Using the Monte Carlo market simulations to find the distribution of S_T, we will be able to calculate option prices for various exercise prices and expiration dates in a manner that is consistent with option pricing theory.

3. METHODOLOGY

The goal of this project is to evaluate how an efficient water market could minimize the municipalities' cost of meeting demand while achieving a desired level of reliability. Two of the primary objectives of this work are to determine what benefit contingent (options) and short-term (spot market leases) transfers could have on the existing market.

Because the market is nascent and little pricing data are available, we must simulate the market activity that would take place if municipalities chose to use the market as their sole source to meet demand. Programs were developed that utilize our knowledge of supply and demand in the Edwards in conjunction with Monte Carlo sampling to simulate activity in the market. Because groundwater rights and the agricultural cycle are defined on an annual basis, the model employs single-year simulations. Given a starting well height in January, the simulation runs through thousands of monthly inflow and outflow scenarios to arrive at an average annual cost of meeting municipal demand for a particular combination of rights, leases, and options. From the results of these simulation runs, we can identify an optimum portfolio of alternative transfers that minimize municipal water supply costs while meeting demand at a desired level of reliability.

In order to simulate market activity, first we must (1) develop a model of the J17 aquifer well to predict cutbacks, (2) model supply and demand on the market to estimate prices in the region, (3) determine the most effective month to exercise options, (4) and develop option prices. After this has been accomplished, a model can be generated which allocates water rights in an optimal manner.

3.1 Modeling the Aquifer

When the J17 well level dropped below 650' in 2000, the emergency drought management rules went into affect for the first time. The rules stated that water users in Bexar and surrounding counties must reduce their usage in that month by 5%. When the well level drops below 640', the users must reduce pumping by 10%, and if the well level drops below 630', another 5% reduction for a total of 15% is required. Since the first mention of the emergency drought management rules over ten year ago, the formulation and implementation of the rules have been under contention. Regardless of the final drought rules, it is clear that the J17 well will be the indicator well that triggers pumping restrictions. If the starting monthly well level in any month is below 650', restrictions will be instituted and the municipalities will be forced to seek additional water supplies on the market. As a result, predicting the level of the J17 well is necessary for determining municipal market demand.

The J17 well is located in San Antonio, in the middle of Bexar County. The daily water level of the well has been logged by USGS since 1932. The 70 years of historical well level data is essential to creating an aquifer model that accurately predicts the starting monthly well levels. A statistical summary of the historical monthly J17 levels is presented in Table 3.1.

Table 3.1: Statistical Summary of J17 Well Levels from 1932-2000

	Historical Monthly J17 Data (ft. above mean sea level)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Height	668.1	668.2	667.8	666.3	665.2	662.8	659.4	657.2	659.6	662.8	665.9	667.5
St. Dev.	13.9	14.1	14.1	14.5	15.8	17.7	17.7	17.3	16.2	15.6	14.9	14.2
Min	626.3	626.0	627.9	625.0	623.6	620.0	617.3	615.3	618.4	619.4	624.1	625.1
Max	692.5	694.0	696.3	695.9	695.1	700.3	692.9	691.2	688.7	693.9	693.2	692.5
% <650	9%	10%	12%	13%	18%	24%	27%	34%	27%	22%	13%	13%
% <640	4%	4%	4%	6%	10%	15%	20%	18%	13%	7%	4%	4%
% <630	1%	1%	3%	1%	1%	3%	5%	10%	6%	3%	3%	1%

Utilizing the previous J17 models described in Chapter 2, it was hypothesized that the height of the J17 well in any month is dependent on the level in the previous month, inflow, municipal pumping, and agricultural pumping. Regressions were run on several proposed models using historical data on recharge, J17 well levels, and discharge. After looking at the R^2, t-stats, and coefficients that resulted from these regressions, the following equation was selected as the best predictor of monthly J17 well levels.

$$H_{t+1} = 144.52 + 0.7965 * H_t + 0.000026 * I_t - 0.000218 * A_t - 0.000355 * M_t + e_t$$

Equation 3.1

Where,

t = month

H = height of the J17 well at the start of the month (ft)

I = inflow into the aquifer (AF)

A = agricultural pumping withdrawal (AF)

M = municipal and industrial pumping withdrawal (AF)

e = error, residuals vary by month (ft)

Table 3.2: Regression Coefficients and T-stats

	Intercept	H_t	I_t	A_t	M/I_t
Coefficient	144.52	0.7965	0.000026	-0.000218	-0.000355
T-Stat	(10.49)	(40.12)	(9.27)	(-7.47)	(-5.96)

* All coefficients are significant at the 99.9% level

* $R^2 = 0.91$

From the t-stats and R^2 value shown above, it is clear that this model fits the historical data fairly well. These regression results reflect the ability of the equation to predict one month ahead. The error term, e, in the model (i.e.- the difference between next month's predicted and actual well height) has a mean of 0, and a standard deviation of 4.9 feet (See Table 3.3). However, as Table 3.3 shows, when predicting next month's well height, the expected error is dependent on which month is being predicted.

Table 3.3: Residuals by Month When Using Equation 3.1 to Predict Well Heights

	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Ave. Residual (ft)	0.84	1.85	2.36	-0.06	-1.42	1.24	0.27	-1.81	-2.96	-1.88	0.58	0.00
St. Dev. (ft)	2.94	2.64	3.79	4.71	7.39	7.58	5.83	4.77	3.65	4.17	2.87	4.90

The average residual in each month, shown in the first row of Table 3.3, is the expected difference between the predicted and actual well height. These values are incorporated into Equation 3.1 to adjust each month's prediction, so that the expected value of the residual is 0 feet in each month.

Equation 3.1 is used to predict well heights up to 11 months into the future (i.e.- from January to December). To see how well this equation can predict well heights for the entire year, Figure 3.1 compares the historic levels of the J17 well versus those predicted by plugging in historic inflows and outflows into Equation 3.1. In Figure 3.1, as in the simulation model, the J17 well level in January is known. The well height in January is used to predict the well heights for that entire year. After predicting the well height for February through December, the J17 level is set to the historic well level in January of the next year, and the process repeats.

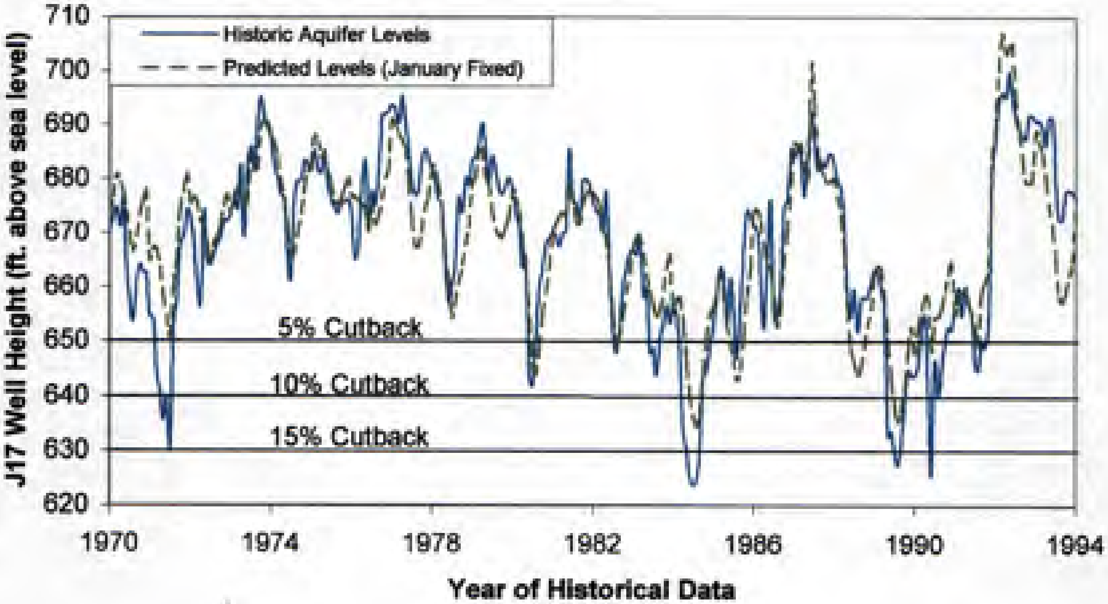

Figure 3.1: J17 Predicted vs. Historical

Using historical data to predict well height results in one discrete value. However, in order to simulate market demand and prices, we want to know the probability that the well level will be above or below the three trigger levels. In order to find the expected

J17 distribution in a future month, we replace the inflow, municipal pumping, and agricultural pumping terms in Equation 3.1 with random variables representing their current probability distribution. The distributions are located in Appendix A.

To assess the accuracy of our forecast models, a simulation was run using the actual January 1999 well height of 686.3'. Figures 3.2 and 3.3 display the results of running a Monte Carlo simulation in which the regressors in Equation 3.1 are replaced by probability distributions and correlation factors (See Appendix A) to predict the well height distributions in March and June, respectively. The year 1999 is selected because it is the most recent year of available data for which recharge and pumping are near average.

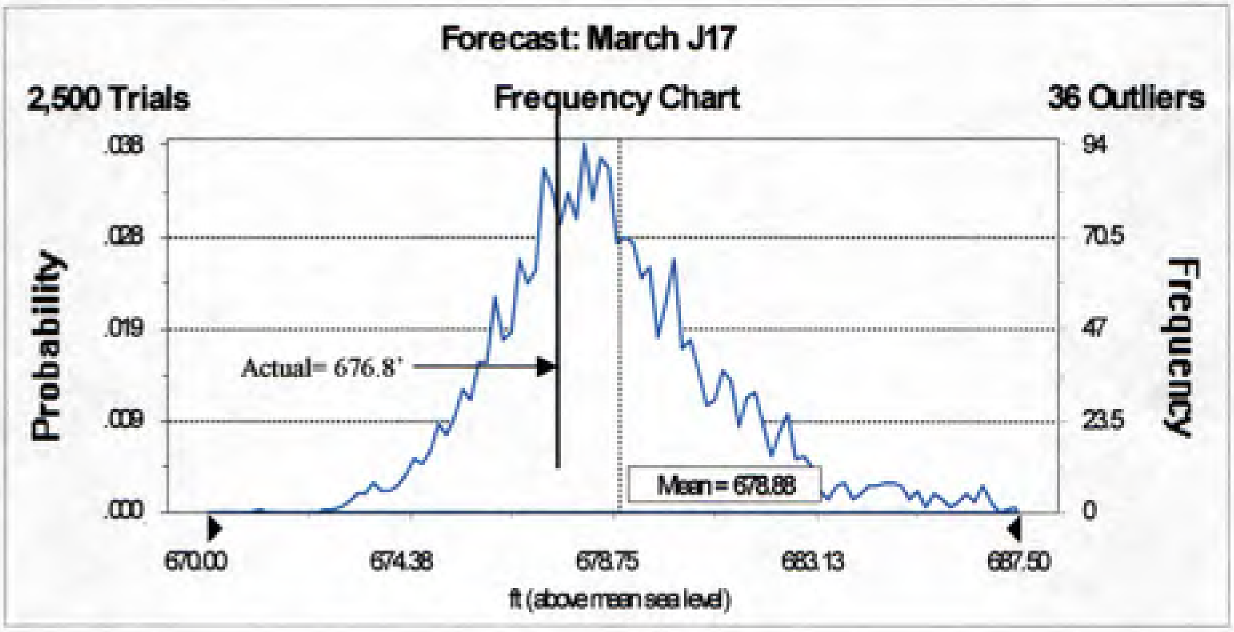

Figure 3.2: Predicting June's Well Height Using January 1999 Well Height

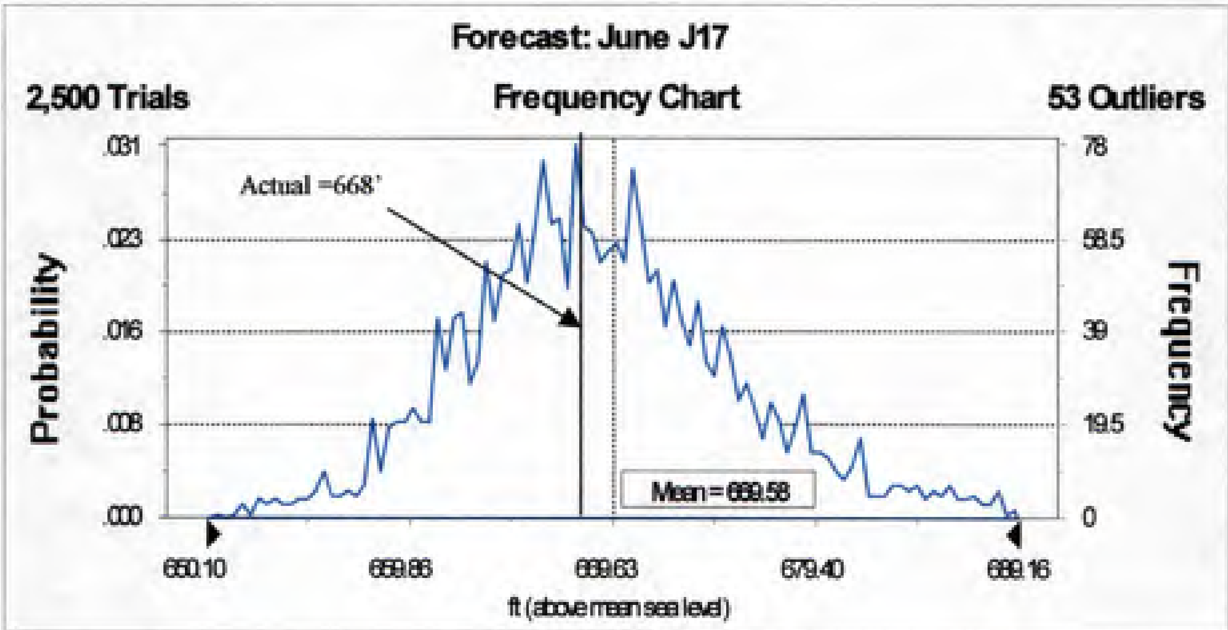

Figure 3.3: Predicting July's Well Height Using January 1999 Well Height

The actual well heights in March and July of 1999 were 676.8' and 668.0', and the mean of our forecasts were 678.9' and 669.6', respectively. Thus, the actual well heights in March and June 1999 were about 2' below our predicted mean height. This level of accuracy is deemed acceptable for our simulations. Also noteworthy is how, when predicting in January, the range of predicted J17 heights broadens from 15 ft in March to 40 ft in June. The ability to better predict aquifer levels (by waiting until later in the year) is one of the advantages of the spot market and contingent transfers proposed in this project.

The results presented in Figures 3.1-3.3 and the R^2 of Equation 3.1 indicate that our aquifer model, despite its relative simplicity, is sufficient for simulating the level of the J17 indicator well. Aquifer modeling is necessary to predict cutbacks and an important factor in determining municipal market demand.

3.2 Water Demand

A model was developed to estimate the lease prices changes that would be experienced in an ideal market under varying degrees of scarcity. In the liquid market, leases can take place in any month of the year, and they last from the month of the transaction through December 31st. The prices reflect the value of the raw, untreated groundwater before it is pumped to the surface.

In order to simulate prices, the demand curves must be established to determine how much water agricultural and municipal users will demand at alternative prices. Although other functional forms are possible, the Cobb-Douglas equation is the most frequently used functional form to model water demand and has been shown to be as effective at explaining the price-quantity relationship as other functional forms (Griffin and Chang 1989). The Cobb-Douglas function is also attractive because it utilizes constant elasticity that is explicitly defined in the equation. As a result, the Cobb-Douglas functional form (See Equation 3.2) was chosen to model demand.

$$Q = \alpha * P^{\varepsilon} \qquad \textbf{Equation 3.2}$$

Where Q is the quantity demanded in acre-feet, P is the price of the water ($/AF), ε is the elasticity, and α is a constant.

3.2.1 Agricultural Demand

Historically, agricultural use in the EA has been highly variable with no clear pattern of increasing or decreasing demand (See Figure 2.3). The variation in agricultural use is primarily due to climatic factors. Forty-five years of annual estimates of irrigation and domestic/stock usage provided by USGS (See Appendix A) were used as the historical agricultural pumping data. In 2000, every irrigator permitted in the EA provided the EAA with an estimate of the typical fraction of his or her total usage in each quarter of the year (i.e. percent used in Jan-Mar, Apr-Jun, Jul-Sep, and Oct-Dec). This information provided the basis for dividing the historic annual usage estimates into quarterly usage estimates. The quarterly estimates were further broken down into monthly usage by looking at the primary crops used in the EA (Texas Agricultural

Statistics Service 1994) and their corresponding irrigation schedule (Texas Agricultural Extension Service 2000).

Probability distributions were then fit to the estimates of historic monthly agricultural, and it was determined from the Chi-Squared Test that the lognormal distribution was the best-fit distribution for each month. Each month's mean, standard deviation, and covariance with recharge and municipal pumping were then input into the simulation model. The percent use, mean, and standard deviation of monthly agricultural usage are shown in Table 3.4.

Table 3.4: Estimated Monthly Agricultural Usage in the EA

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percent Use	5.8%	5.8%	5.8%	12.2%	18.3%	18.3%	13.1%	10.2%	5.8%	1.6%	1.6%	1.6%
Mean (AF)	6,289	6,289	6,289	13,312	19,989	19,989	14,352	11,162	6,379	1,730	1,730	1,730
St.Dev.(AF)	3,005	3,005	3,005	6,360	9,550	9,550	6,857	5,333	3,048	827	827	827

In order to predict how agricultural use will change after the implementation of a market, we must establish the monthly agricultural demand functions. In 2000, the EAA issued the agricultural sector 247,000 AF of annual permits based on historical use information submitted by the EA farmers. The cost to use the irrigation water is essentially the cost of pumping the water out of the ground. In 1988, Fulton and Dillon determined the average agricultural pumping cost to be approximately \$22/AF (McCarl, Dillon et al. 1993). Using the consumer price index to adjust the 1988 dollars to 2002, the average pumping cost in present value dollars is approximately \$35/AF. This price (\$35/AF) and permit quantity (247,000 AF/yr) make up a known point on the annual agricultural demand curve. Although the base point is known, the agricultural elasticity still needs to be determined in order to estimate the constant, α, in the Cobb-Douglas equation and fully specify the demand function.

In order to predict how farmers will react to various prices on the proposed water market, we must estimate the price elasticity of demand from previous studies in the region. Using the Cobb-Douglas form, Characklis et al.(1999) found the annual elasticity of field crops in the Lower Rio Grange region of Texas to be –0.7. Similarly, a study in the High Plains region of Texas (Nieswiadomy 1985) using Cobb-Douglas calculated the annual elasticity of irrigation water as –0.8. Due to the limited amount of information regarding agricultural elasticity in the EA, the agricultural elasticity at the start of the year in our simulation model is estimated as –0.8.

Although there is not plentiful data on agricultural elasticity in the EA, Keplinger et al. (1998) have analyzed the marginal value of agricultural water at different times of the year in the EA. Their results indicate that agricultural elasticity is significantly more inelastic in June than in January. The demand becomes more inelastic in the summer (i.e.-less responsive to price changes) as a result of planting. Figure 3.5 displays how the farmer's cumulative production costs jump after planting in February. The high cost of planting is a sunk (unrecoverable) cost that causes the agricultural demand to become more inelastic.

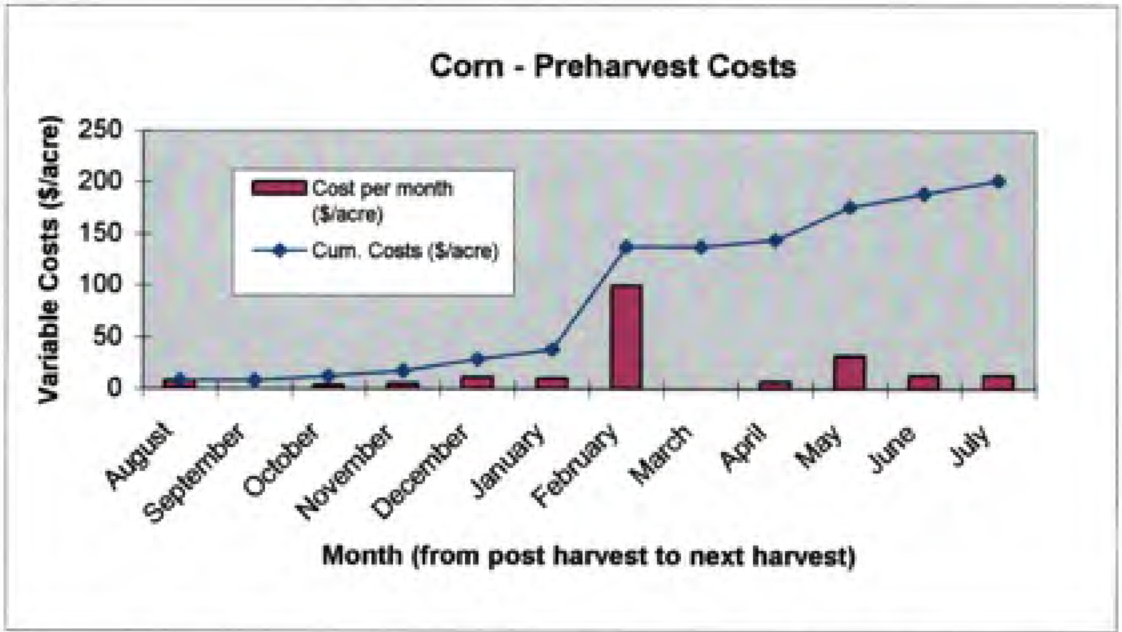

Figure 3.4: Costs of Harvesting Corn in the EA(Texas Agricultural Extension Service 2000)

Nearly 75% of irrigated land in the EA is used for corn or Bermuda grass (Keplinger 1998; Hernandez 2002). Bermuda grass is repeatedly harvested throughout the year and does not experience a significant jump in cost; however, 50% of the annual cost of harvesting corn occurs during the last week in February (Texas Agricultural Extension Service 2000).

As a result of the large amount of sunk costs that farmers incur once planting has occurred, it is expected that the demand curve will be more inelastic in the summer time. Fitting a Cobb-Douglas curve to the data from Keplinger et al.(1998) indicates that agricultural elasticity in June is in the range of –0.27 to –0.49. Although the June demand curve for the western counties was not estimated by McCarl and Keplinger, their results indicate the western agricultural users display more inelastic behavior than the eastern users (Keplinger 1998). Therefore when factoring the response of the western counties, the June agricultural elasticity is more likely closer to –0.27 than –0.49.

Because of the drastic cost increase at the end of February, displayed in Figure 3.4, and because corn is the primary crop in the EA (Texas Agricultural Statistics Service 1994), the elasticity in our model switches from –0.8 to –0.3 in March, to be consistent with the June elasticity derived from Keplinger et al.'s (1998) work. Generally, harvesting of crops occurs before October, at which point the agricultural cycle begins again. Therefore, the agricultural elasticity in the simulation model switches back to –0.8 for October-December. These elasticities will be used in conjunction with supply and usage data to establish the monthly agricultural demand curves.

3.2.2 Municipal Demand

Municipal demand is simulated in our model in order to predict the J17 well levels and total market demand. Currently, municipal water use is around 270,000 AF, approximately double what is was 45 years ago. Municipal pumping has seen growth rates in the last few years of around 1.1% per year (Keplinger 1998). However, with the cap at 450,000 AF (reduced to 400,000 AF in 2008) and the restrictions on agricultural sales[6], municipal pumping from the aquifer will not continue to grow in a linear manner. The municipal usage distributions shown in Appendix A are based on 30 years of monthly SAWS data and 45 years of annual data provided by USGS that have been adjusted for current pumping rates. Although total municipal pumping has increased

[6] Although still under debate, a proposed rule states that 1 AF per acre of historically irrigated land must be retained for irrigation. As of 1996, there was approximately 80,000 acres of irrigated land in the region.

steadily each year, per customer usage has been fairly constant since 1990, with the exception of the irrigation suspension year in 1997 (See Figure 3.5). The 30 years of per customer information provided by SAWS was normalized to reflect the per customer usage seen in the 1990s. The normalized per customer usage was then multiplied by the estimated 408,000 municipal customers in the EA (Hernandez 2002) to provide a distribution of municipal demand that reflects the current usage.

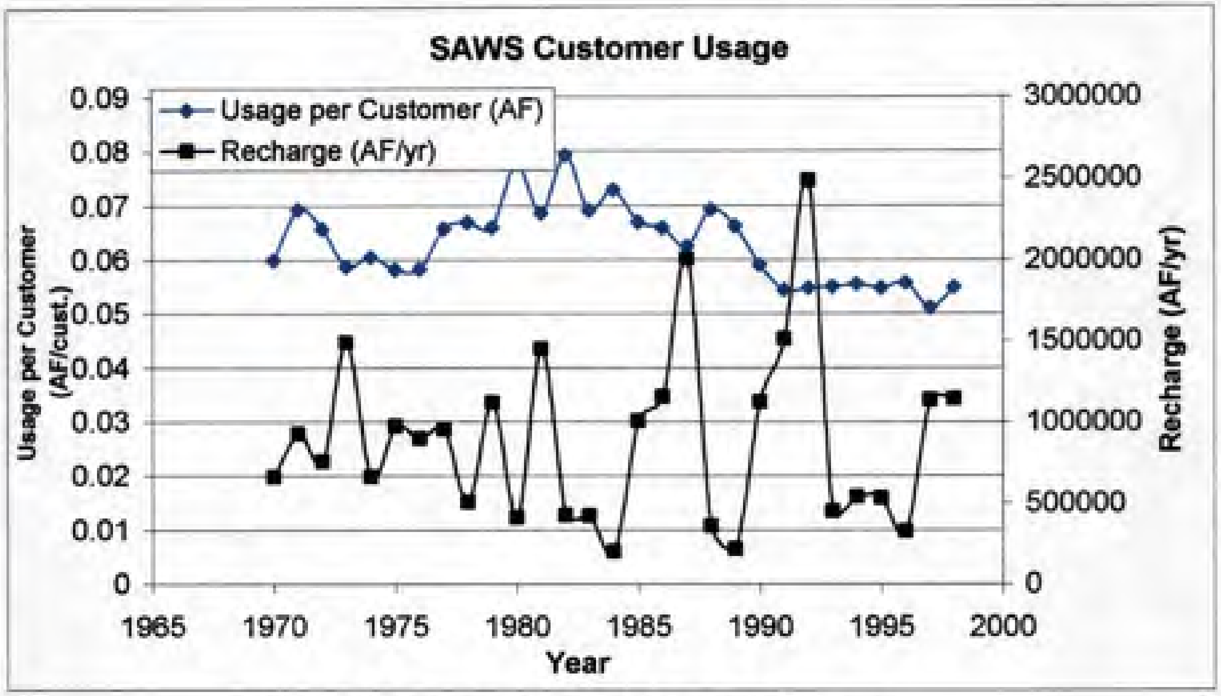

Figure 3.5: Per Customer Usage and Recharge

Municipal demand elasticity for the EA region was based on research by Griffin and Chang (1989) and the other studies detailed in Chapter 2. The municipal elasticity is estimated as –0.35. The average price charged by SAWS is \$1.32/kgal, or \$430/AF[7], and the average annual municipal usage is estimated as 270,000 AF/yr. The elasticity is used in conjunction with this information to derive the constant, α, required to fully specify the Cobb-Douglas demand function.

[7] This price is based on 1999 SAWS data. The price will rise to near \$2/kgal in the near future as SAWS' customers are assessed a water supply fee that will be used to finance planned expansion projects (SAWS 2002).

3.3 Water Market

The municipal permitted amount is much less than they typically use in a year. As, municipalities place a much higher value on water than agricultural users, the vast majority of market transactions currently occurring in the EA involve water transfers from agricultural users to municipalities. Therefore, the supply on the simulated market is assumed to be the available number of agricultural permits (less any that have been transferred), and the demand on the market is the total municipal demand minus the number of rights, leases, and options owned by the municipalities. So, the supply of raw water available to be transferred in any month, $Supply_i$, is estimated as the annual amount of water allocated to the agricultural sector less what has already been used or sold in that year.

$$Supply_i = AGIRP - \sum_{j=1}^{i-1} AgUse_j - \sum_{j=1}^{i-1} Leased, Sold, Optioned_j \qquad \textbf{Equation 3.3}$$

Where $AgUse_j$ is the agricultural demand in month j. This water has already been consumed by farmers and cannot be sold. AGIRP is the number of agricultural permits at the beginning of the year. The intersection of the agricultural demand curve with their supply line indicates the value of the water to the agricultural users. To estimate the demand curve at the start of the year, we can use the base point (Q = 247,000 AF/yr and P=\$35/AF) and the elasticity (-0.8) described in Section 3.2.1.

Using this elasticity and the known base point, the constant, α, in the Cobb-Douglas function can be calculated.

$$\alpha = Q / P^{\varepsilon} = 247{,}000 / 35^{-0.8} = 4245720 \qquad \textbf{Equation 3.4}$$

Therefore, the annual agricultural demand function in January is

$$Q = 4245720 * P^{-0.8} \qquad \textbf{Equation 3.5}$$

In order to reduce the number of permits from 532,000 AF to 450,000 AF, the EAA is purchasing EA permits and retiring them. Due to the disparity in the value of water between agricultural and municipal users and the fact that municipal users demand far in excess of their permitted amount, it is assumed that the permits being purchased by the EAA are coming solely from agricultural users. Selling these 82,000 AF reduces the amount of available agricultural permits on our market from 247,000 AF to 165,000 AF. By reducing supply, the value of agricultural water increases (See Figure 3.7). Now the value of water in the agricultural sector is:

$$P = (Q/a)^{(1/e)} = (165{,}000/4245720)^{(1/-0.8)} = \$57.95/AF \qquad \textbf{Equation 3.6}$$

Figure 3.6 displays the price increase from P1 to P2 when the agricultural users sell the 82,000 AF. The remaining 165,000 AF of agricultural permits are valued at $58/AF. However, this price reflects the value of the water at the surface, and our market deals with water still in the ground. Therefore, to find the market price, this value must be reduced by the $35/AF cost of pumping the water out of the ground. This adjustment will be explained in more detail in following section.

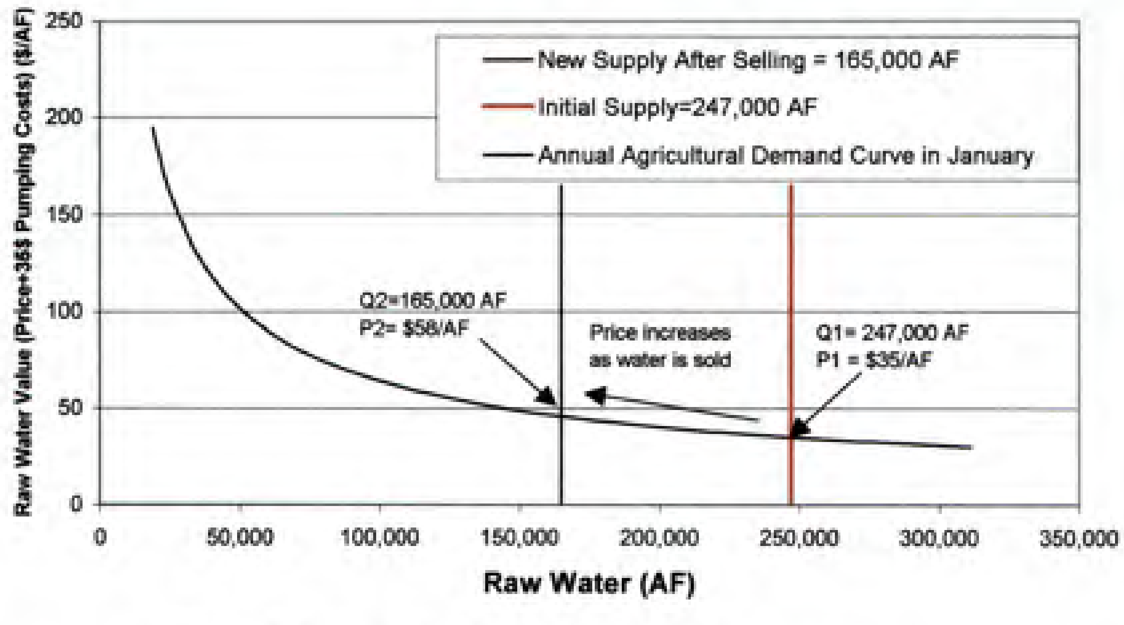

Figure 3.6: Agricultural Demand Curve in January

The point indicated by (Q2, P2) is the starting point for each year-long simulation run. Q2 is the expected agricultural permit quantity in the near future after the EAA finishes buying down the number of rights to 450,000 AF. Thus, we are simulating conditions due to occur in the next 1-3 years in an attempt to provide municipalities with a cost effective solution that delays the need for capital expansion projects and/or provides a way to meet short-term demand while physical assets are being built.

As the agricultural sector uses water throughout the year, their demand and supply are reduced, which causes the demand and supply curves to shift to the left.
Also, as the municipality buys, options, or leases rights from the agricultural users, the supply of agricultural rights decreases, causing the supply line to shift left. This moves the intersection point further up the demand curve and increases the value of the water.

Given the low profitability of crop production, there may be a choke price for the agricultural sector above which demand is nonexistent. This results in a perfectly elastic region of irrigation demand, indicating that activity ceases entirely or converts to dryland farming. In the economic analysis of the EA, Keplinger et al. (1998) found irrigation demand to be nonexistent if a price of $100/AF was offered at the start of the year. However, later in the year, this price is likely to be higher, therefore, choke price of $200/AF was determined to be a reasonable and conservative value in our simulations (as indicated by the horizontal portion of the agriculture demand curve in Figure 3.8).

The J17 well level triggers monthly restrictions in municipal pumping. Therefore, municipal market demand will vary by month, depending on the height of the well. Determining how much the municipalities will purchase from the agricultural users requires establishing their monthly demand curves. When estimating municipal reaction to price changes, one must remember that municipal market demand is only a fraction of their total demand. For example, municipalities own 227,000 AF of rights. In an average year, they use around 270,000 AF, which means they must buy approximately 45,000 AF on the market, or ~17% of their total water supply. So an increase in water cost as a result of making up a shortfall will only raise consumer prices proportionately. To illustrate this point, the effect of a relatively high lease price of $100/AF is described below.

At a lease price of $100/AF, the cost per thousand gallons (kgal) is $0.31/kgal.

Only 17% of the municipal water supply costs this amount, so, assuming average cost pricing, the cost increase for the customers is \$0.31/kgal*0.17= \$0.052/kgal. If the current price is \$1.32/kgal, this represents an increase of ~ 4%. With an elasticity of –0.35, the expected change in quantity demanded is –0.014, or a 1.4% decrease. Due to the small magnitude of the change and the fact that most trades take place at prices that are lower than \$100/AF, the municipal market demand in the simulation runs is modeled as completely inelastic.

3.3.1 Raw Water Market

The water transferred on the market is the raw, untreated groundwater. However, the agricultural demand function described earlier is for water already pumped out of the ground and the municipal demand is for the treated commodity delivered to the tap. Putting both municipal and agricultural water demand into comparable form requires that both be traced back to a common point of reference (Characklis 1999). In this case, the common point of reference is the water in the ground. Because all points within the EA are considered to be the same under current rules (i.e.- pumping in one place is the same as pumping in another), only water rights and not actual water needs to be transferred. Therefore, there should be minimal transaction losses or costs associated with market transfers.

In order to put demand in terms of raw water, the agricultural demand curve must be shifted down by the \$35/AF pumping cost. Similarly, prices on the municipal curve must be reduced by the \$430/AF in pumping and treatment costs that customers currently pay. Because of the assumption that municipal market demand is completely inelastic, the municipal demand curve will be a vertical line. Figure 3.7 displays the demand curves adjusted for the cost of delivery. For illustrative purposes, it is assumed that the municipal market demand in January is equal to their average shortfall, 45,000 AF. This completely inelastic municipal market demand (blue vertical line in Figure 3.7) shifts the agricultural curve to the right by 45,000 AF to create the aggregate market demand curve.

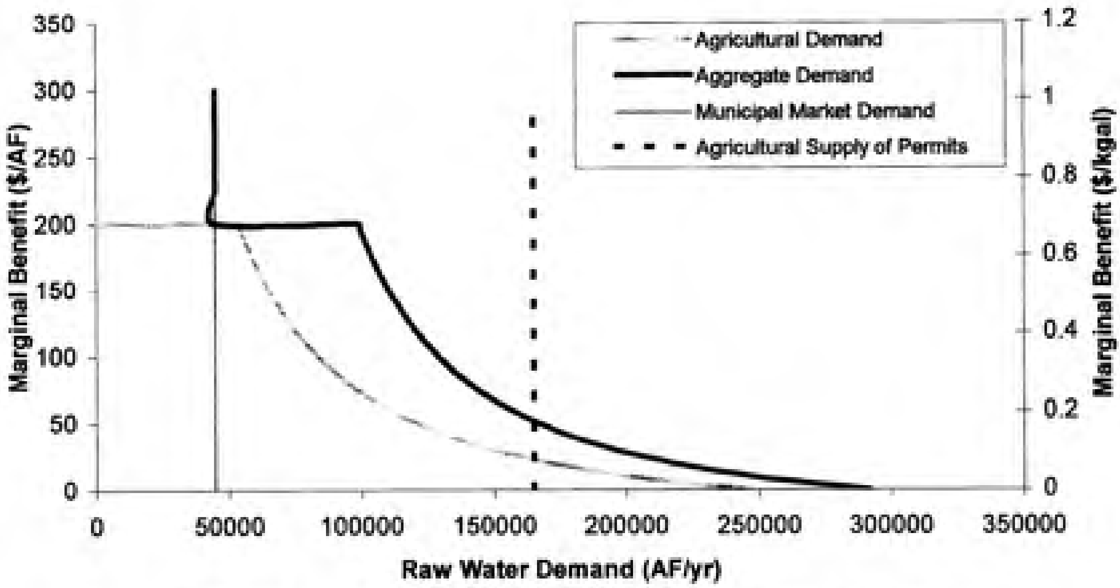

Figure 3.7: Agricultural and Aggregate Demand Curves

The vertical line at 165,000 AF is the market supply line, i.e.- the number of remaining agricultural permits after the EAA buys down their total amount from 247,000 AF. The intersection of the supply line with the agricultural demand curve represents an estimate of the marginal benefit of the raw water to the agricultural users ($/AF/yr). As indicated in Figure 3.7, the marginal value of water in the agricultural sector is approximately $25/AF. The intersection of the aggregate demand curve with the supply line, $50/AF, indicates the market lease price of raw water in January, if the municipalities demand 45,000 AF. The figure represents a deterministic version of the supply and demand in the EA that results in a single lease price. In the market simulations agricultural and municipal demand are stochastic functions that lead to a probability distribution of lease prices.

With the monthly elasticities, demands, and supply distributions known, a spot market lease price distribution in any month can be found using Monte Carlo simulation. These lease price distributions will determine the price of options, explained in the following section, and will dictate the optimal portfolio of market alternatives found through the simulation model.

3.3.2 Option Pricing

Because options are a new element in the EA, no prices or framework for options exist. The following analysis is used to determine the exercise month, option prices, and exercise amount for the market simulations.

Selecting Exercise Month

The municipal market demand distributions developed from the simulation model can help determine which month will be the best exercise month. The exercise month should be early enough in the year so that the majority of shortfalls have yet to occur and so that agricultural users still have water left to sell. However, an exercise month earlier in the year reduces our ability to predict the cumulative shortfall from the exercise month through the rest of the year.

As explained in the previous section, several different quantities of options are tried in various market portfolios, and the average cost to meet reliability is calculated for each portfolio. However, this does not address the decision of how many options to exercise. To make this decision, the simulation model predicts the shortfall and consequent spot market lease price distribution from the exercise month through the rest of the year. If the expected spot market price is greater than the exercise price, then we exercise our options up to our expected shortfall amount. A simplified version of the decision is given below:

$$E(Shortfall_i) = \sum_{j=1}^{xm-1} MD_j + \sum_{j=xm}^{i} E(MD_j) - Buy - \sum_{j=1}^{xm} L_j - \sum_{j=xm}^{i-1} Shortfall_j$$

For i = xm:12

If $E(LP_i) > XP_i$ then $X_i = Shortfall_i$ **Equation 3.7**

Where MD is municipal demand, XM = exercise month, LP = Lease Price, L = spot market leases, XP = Exercise Price, X_i = amt. of options needed in month i. The sum of all X_i's is the number of options that will be exercised.

Forecasts of shortfalls (and spot lease prices) will enable us to determine the optimum number of options to exercise. The confidence in the model's shortfall predictions is largely tied to our ability to calculate the J17 well height. Table 3.5 displays some statistics of the J17 well using 68 years of USGS data.

Table 3.5: Monthly Statistics for the J17 Indicator Well

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ave. Well Height (ft)	668.1	668.2	667.8	666.3	665.2	662.8	659.4	657.2	659.6	662.8	665.9	667.5
St. Dev. (ft)	13.9	14.1	14.1	14.5	15.8	17.7	17.7	17.3	16.2	15.6	14.9	14.2
Prob <=650	0.09	0.10	0.12	0.13	0.18	0.24	0.27	0.34	0.27	0.22	0.13	0.13

We would like our exercise decision to occur right before cutbacks were most likely to start taking place. Historically, August has a 34% probability of being below 650', the highest of any month of the year. However, in any month from June to October, the probability of a cutback is above 20%. Table 3.5 also indicates that June and July have the highest standard deviation in well level. This generally makes the well levels in these months the most difficult to predict, and therefore, we could more accurately forecast shortfalls if we waited until the heights in June or July were known.

The results from the regression analysis also support the conclusion that June and July are the hardest to predict. Table 3.6 displays the average and standard deviations of the residuals when using Equation 3.1 to estimate the J17 well level in the next month.

Table 3.6: Residuals from Predicting the Next Month's Well Height

	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ave. Residual (ft)	0.84	1.85	2.36	-0.06	-1.42	1.24	0.27	-1.81	-2.96	-1.88	0.58
St. Dev. (ft)	2.94	2.64	3.79	4.71	7.39	7.58	5.83	4.77	3.65	4.17	2.87

The highest residual standard deviations are in June and July, which means that these months are the most difficult to predict their starting well level when given the starting well level of the previous month.

Using Equation 3.13, we can run the simulation model to predict the cumulative shortfall from the exercise month through the end of the year. By comparing the prediction to the actual number of leases that occur between the exercise month and end of the year, we can get an idea of the capacity to predict shortfalls using various exercise months. Figure 3.8 displays the results of running the market simulation using an exercise month of March, June, and July. March is chosen because of its significance in the agricultural cycle. Typically, planting occurs around this time, which causes the agricultural elasticity to become significantly more inelastic. The curves shown below represent the distribution of error in predicting the cumulative shortfall, i.e.- total number of spot leases from the exercise month through the end of the year minus the predicted cumulative shortfall.

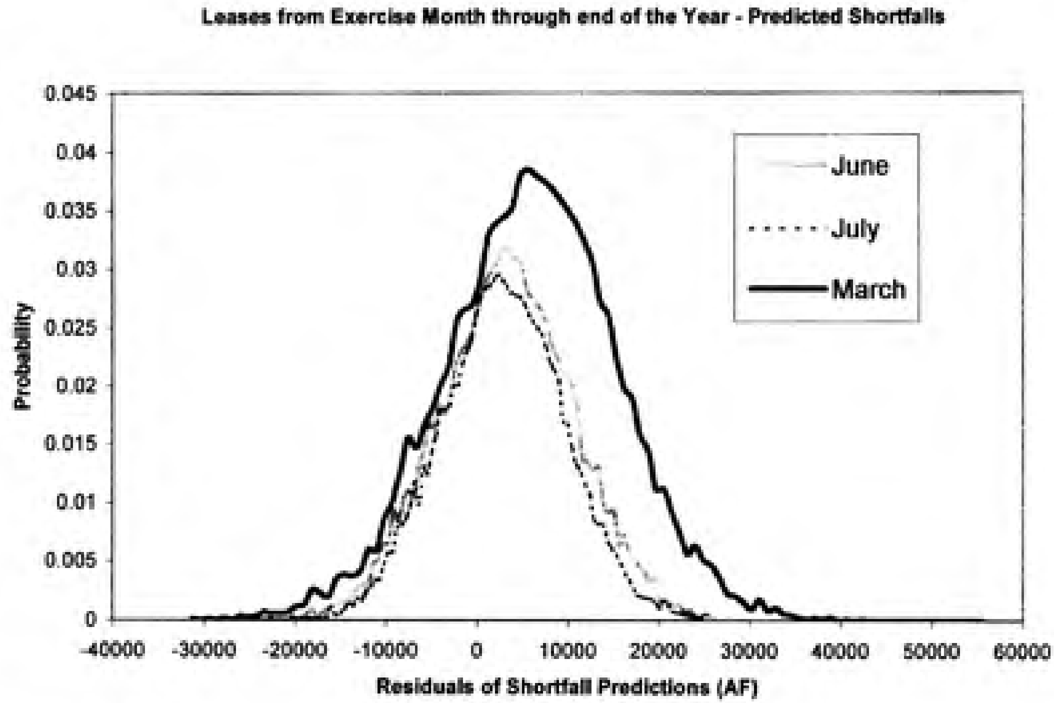

Figure 3.8: Comparing Shortfall Prediction Accuracy with Exercise Month

In Figure 3.8, the June and July distributions are smaller and narrower than the March curve. This results from our increased ability to predict shortfalls from June and July through the end of the year than from March through the end of the year. The reason the June and July curves have a smaller area is because there is a spike at zero that is not portrayed by the interpolated distributions in Figure 3.8. Although the improvement from

March to June or July is very noticeable, there is not a significant difference between June and July.

Because June and July are the most difficult months to predict and because, historically, well levels in these months are below 650'a significant percent of the time, it seems logical to select one of these two months as the exercise month. When deciding which month to set as the exercise month, we must take into account the knowledge available in the exercise month as well as the agricultural water remaining. From Figure 3.8, we can see that there is not a large improvement in predictive ability in July rather than June. Also, June is the peak month for agricultural use, which means there is ~20,000 AF less water available in the agricultural sector in July than in June. Due to these factors, June appears to be the optimal month to select as the exercise month for our market simulations.

Calculating Option Prices

Because options are a new element to the Edwards Aquifer, no prices for options exist. In our simulated market, we have the ability to purchase options in January with the "option" to call (i.e.- use the water) in the exercise month of June. Utilizing option pricing theory explained in Section 2.5 and the Monte Carlo simulated lease price distributions, we can calculate an option price for any given exercise price from the equation below.

$$c = e^{-r(T-t)} * E[\max(S_T - XP, 0)] \qquad \textbf{Equation 3.8}$$

Where S_T is the price in the exercise month, T, and XP is the exercise price. The simulated lease price distributions give us several thousand estimates of S_T. For each simulated value of S_T, we can calculate $max(S_T - X, 0)$. The expected value of $max(S_T - X, 0)$ can be estimated as the average of these values. Assuming the growth rate, r, is known, we can then choose an exercise price and find the expected value of $max(S_T - X, 0)$. From this we calculate the option price, *c*.

Running the Monte Carlo simulation for a given January well height provides us with a distribution of lease prices in June, S_T. Utilizing an r of 0.05, Equation 3.8, and the simulated June lease price distribution, the option and corresponding exercise prices displayed in Table 3.7 are obtained.

Table 3.7: Option and Exercise Prices: January Buy, June Call

Option Price ($/AF)	June Exercise Cost ($/AF)		
	Jan. J17=650'	Jan. J17=670'	Jan. J17=685'
10	74	73	73
15	62	60	60
20	50	49	48
25	42	40	39
30	34	32	31

In the simulation model, the option price is selected beforehand, and then the exercise price that corresponds to the option price and January well level is inputted into the model. In the simulation results presented in Chapter 4, and option price of $20/AF was used, and consequently, the exercise price is between $50-$48/AF depending on the January well level. The amount of options to exercise is determined by predicting the shortfall and lease price from June through December as shown in Equation 3.7. The objective function, constraints, and other equations used in the market simulations are described in the following section.

3.3.3 Market Simulations

Simulation programs (developed in *Matlab*) seek the optimal portfolio of market alternatives to meet municipal demand subject to a desired level of reliability. Our objective function is to minimize the expected municipal water supply costs. The cost of meeting demand through the market is given by:

$$C = (BuyP * Buy) + (OpP * Op) + (XP * XD) + \sum_{j=1}^{12} LP_j * L_j \qquad \textbf{Equation 3.9}$$

Where,

P	* A "P" after the variable refers to the price of that alternative
Buy	* Amount of Rights to Buy at the start of the year.
Op	* Amount of Options to Buy in January with June call date
XD	* Amount of Options to exercise in June
L_i	* Amount of Leases to purchase on the spot market in month i

The amount of rights to buy, option, and annually lease are the decision variables in the model. Essentially, spot market leases represent a slack variable. The amount of water to lease on the spot market, L_i, is determined by reliability constraints. So, in total, there are four alternative sources for meeting water demand: rights, annual leases, options, and spot market leases. (Simulations that used less market alternatives are explained in Appendix C). The typical ranges of prices simulated on the market are shown in Table 3.8.

Table 3.8: Typical Simulated Prices of the Market Alternatives

	Price ($/AF)
Rights ($/AF/yr)	40-45
Annual Leases	45-65
Option Price	20
Exercise Price	45-50

	Spot Lease Price ($/AF)
Range	5-200
Ave. January	45
Ave. June	65

"IF" statements are utilized to employ reliability constraints in the simulation model. Whenever a constraint condition (written as an "if" statement) is not met, an action is taken to remedy the failure. The primary constraints in the model are the reliability and maximum failure constraints shown below:

Monthly Reliability Constraint:

$$P[\sum_{j=1}^{i} IRP_j + \sum_{j=1}^{i-1} L_j + Buy + \sum_{j=1}^{i-1} X_j \geq \sum_{j=1}^{i} MD_j] \geq R \qquad \textbf{Equation 3.10}$$

where R is the desired probability that the municipality will meet monthly demand. MD_j is the municipal demand in month j, and IRP_j is the number of permits granted to the municipality for month j. Xj is the amount of exercised options that are used in month j. The sum of Xj is less than or equal to the total number of exercised options, XD.

The bought rights, *Buy*, are allocated throughout the year in a manner that equalizes the probability of failure in any given month. This assumed allocation is consistent with what municipalities would do because is maximizes the benefit to the municipality. If the bought rights were not distributed throughout the year, the municipal failures would primarily happen in November and December when the bought rights were used up. This could lead to very large failures in the latter months, which is a problem because at the end of the year agricultural users do not have much water left to sell and the average lease price is higher. To prevent these large shortfalls, the model also constrains the magnitude of the allowable failure.

Max Failure:

$$\sum_{j=1}^{i} MD_j - \sum_{j=1}^{i} IRP_j - \sum_{j=1}^{i-1} L_j - Buy - \sum_{j=1}^{i-1} X_j \leq F \qquad \textbf{Equation 3.11}$$

where F is the maximum allowable monthly shortfall.

The model works as an optimization by simulation approach. The program searches many combinations to find the amount of annual leases, options, and rights that minimizes the expected cost of meeting demand. The cost depends on the selected level of reliability and the starting January well level, which are set a priori. The quantity of spot leases purchased in any given month is determined by the reliability constraints. If a shortfall occurs in a month that causes the either the monthly reliability or maximum shortfall constraint to be exceeded, spot market leases are purchased in order to meet this constraint. In this way, the simulation model can employ the reliability constraints in a fashion similar to how they would be used in an optimization program. The number of options to exercise at the time of expiration is determined by calculating the expected shortfall and lease prices from the exercise month through the end of the year, as explained in the previous section.

Because rights can be bought in perpetuity and the simulations are only one year in duration, a separate decision for finding the optimal number of rights was required. In order to establish the optimum number of rights to buy, the model was run at the average January starting well level of 670' with different amount of rights being bought in each simulation scenario. This is the expected value of the January well height, and therefore, on average, this is the annual situation that the municipalities will face. Over many trials the number of rights that resulted in the lowest cost began to converge to a value, and that value was selected as the optimum level of rights to buy.

With the number of rights established, the optimum level of options and annual leases can be determined. A grid of annual lease and option combinations is defined at the start of the model. The model selects the first pair of annual lease and option values and runs through the simulation, calculating the cost to meet annual demand in the manner shown in Figure 3.9.

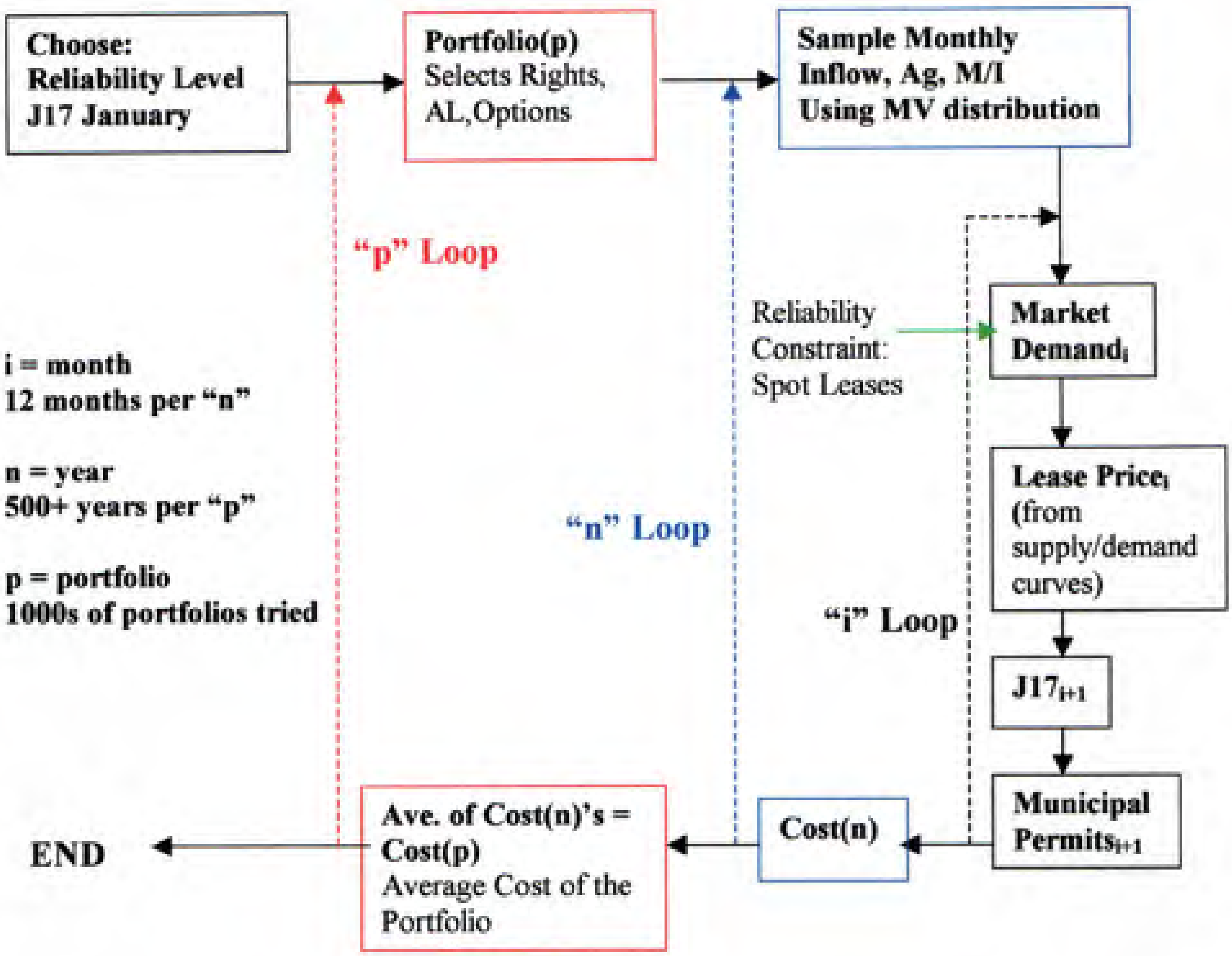

Figure 3.9: Flow Chart of Simulation Process

After selecting the combination of annual leases and options from the predefined grid of choices, all twelve months of inflow, agricultural use, and municipal use are selected using Monte Carlo sampling from a multivariate joint distribution. This is referred to as the recharge/discharge scenario. In conjunction with the reliability constraint and cutbacks, these sampled quantities determine monthly market demand. After selecting the recharge/discharge scenario, the model enters the month loop indicated by an "i" in Figure 3.9. Starting in January, if municipal monthly demand exceeds its supply and fails to meet the reliability constraints, the municipality must exercise options or go to the spot market to make up the shortfall. The spot market lease price distributions for each month are found using the demand curves in the manner described earlier and recapitulated below.

The agricultural demand curve in any month is given by:

$$Q = \alpha * P^{\varepsilon}$$

Therefore, the price in any month is:

$$P = \left(\frac{Q}{\alpha}\right)^{1/\varepsilon}$$

Where Q is the quantity at which the supply line and demand curve intersect, as given by Equation 3.3. Substituting Q with the equation for market supply (See Equation 3.3), we arrive at the spot market lease price in month, i:

$$LP_i = \{[AGIRP - Buy - \sum_{j=1}^{i} L_j - \sum_{j=1}^{i} X_j - \sum_{j=1}^{i-1} AgUse_j]/\alpha_i\}^{1/\varepsilon_i} - 35 \qquad \textbf{Equation 3.12}$$

where, $AgUse_i$ is the amount of water used by irrigators in month **i**.

The monthly agricultural use is generated using Monte Carlo sampling and then is adjusted to reflect market transfers that occur in that month. Also, as shown in Equation 3.12, in order to put the lease price in terms of raw water in the ground, we must subtract the $35/AF pump cost use to generate the demand curve.

Although the market prices are based on supply and demand theory, they are also dependent on the response of the agricultural and municipal users in the region. The lease price will increase during dry months in which water demand is above average, and decrease during wet months when agricultural use and municipal market demand are low. However, price data from other markets indicate that people/markets respond relatively to these changes in agricultural and municipal demand. This is particularly true for a commodity like water for which most decisions are long term. As a result, there is likely to be a dampening in the month-to-month variation in lease price.

To make our simulations reflect this, the change in lease price from one month to the next is limited based on behavior observed in a nearby water market in the Lower Rio Grande Region. The current Edwards water market has seen little fluctuation in lease price (Water Strategist 2001)[8] and the estimated range of the value of water rights in the Edwards is only \$30AF/yr (Edwardswater.com 2001)[9]. In the Lower Rio Grande region, located just south of the EA, there is monthly leasing of water rights within the municipal and agricultural sectors (but not between sectors). From January 1994-2000, the maximum increase in lease price from one month to the next was \$20/AF in the agricultural sector and \$15/AF in the municipal sector. The maximum decrease between months was \$10/AF in the municipal sector and \$15/AF in the agricultural sector. The relatively low level of volatility in the Lower Rio Grande market along with the lack of volatility seen in the EA annual lease price resulted in the implementation of monthly lease price change restrictions in our model. In the EA market simulations, the maximum allowable monthly increase in lease price is \$20/AF and the maximum decrease is \$10/AF.

After the leasing and exercising decisions in January have been made and the spot market lease price has been calculated, the constant, α, in the Cobb-Douglas agricultural demand function for the February is calculated.

$$\alpha_{i+1} = (AGIRP - \sum_{j=1}^{i} AgMean_j)/((LP_i + 35)^\wedge(\varepsilon_{i+1})) \qquad \textbf{Equation 3.13}$$

where *AGIRP* are the number of rights owned by the agricultural users and $AgMean_i$ is the expected use in month i.

Then, the well height in February is calculated using the municipal, agricultural, and recharge values from January.

$$H_{i+1} = 144.52 + 0.7965 * H_i + 0.000026 * I_i - 0.000218 * AgUse_i - 0.000355 * M_i + e_i$$

Equation 3.14

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[8] SAWS has paid \$75-80/yr for their leases on the water market.

[9] Edwardswater.com cites the South Central Texas Water Plan Group as valuing the pumping rights at \$51-80 per year.

If the J17 height is less than 650', the available municipal permits, IRP_i, in that month are reduced according to the emergency drought management rules, leading to an increase in market demand.

The month index, i, is then changed to i+1, and the model returns to the top of the program and repeats until the entire year has been completed. Once the year has been simulated, the annual cost is calculated as given by Equation 3.9. This gives the cost using a particular market portfolio to meet a selected level of reliability under one discharge and recharge scenario. However, we want to know the expected cost of meeting demand for a given market portfolio over all possible recharge and discharge events. Therefore, the program repeats using the same market portfolio, but the monthly demands and recharges change (through Monte Carlo sampling). The demands[10] and recharge values are sampled randomly from their distributions, and the spot market leases adjust automatically to meet the reliability constraints. After 500+ simulations using the same market portfolio (the number of rights, annual leases, and options stay the same, but exercised options and spot leases vary), the annual costs are averaged to find the expected cost of meeting demand for this particular set of decision variables. The program then selects a new set of annual leases and options, and the entire process is repeated.

At the end of the simulation, approximately 1000s of portfolios have been tried, each having been run over 500 times at different recharge and discharge levels. From these portfolios, we can find the market portfolio that minimizes the average cost of meeting demand for the given starting well height and reliability level.

[10] This program is set up to meet the immediate annual needs of the municipalities, based on current demand information. However, demand can be changed to model future years as population increases.

4. RESULTS AND DISCUSSION

Currently, water transfers in the Edwards consist of permanent transfers of rights and single or multi-year leases. Adding shorter term and contingent transfers, such as spot market leases and options, to the available market alternatives will allow municipalities to delay their decision commitments until later in the year when more information regarding shortfalls is known. This improved information should decrease the quantity of water needed by the municipalities to meet their desired level of reliability. In turn, this reduction in water supply quantity should translate into cost savings for the municipality.

The market alternatives under consideration in this project are rights, annual leases, options, and spot market leases. Ultimately, the market that develops in the EA may use all of these alternatives or continue using only rights and multi-year transfers. The results presented in this section address the various market types that may develop in the EA, from the simplest market that utilizes only permanent transfers to the ideal market that is totally liquid.

In order to simulate and evaluate each potential market type, some critical assumptions had to be made regarding how the drought management rules will be enforced. If the height of J17 indicator well drops below 650', pumping restrictions are implemented for users in the San Antonio area. It is assumed in these analyses that restrictions are based on the well level at the start of the month and last for the duration of that month. It is also assumed that the cutbacks dictated by the drought rules (5%, 10%, and 15%) are based on a percentage of the user's typical pumping amount in that particular month and apply only to the user's rights granted by the EAA (not to market purchases).

Because the rules are written in regards to monthly usage, the ability of the municipality to meet monthly demand (rather than annual) was used as the measure of reliability. Assessing the ability of the market instruments to meet monthly reliability is inherently more complicated than assessing annual reliability due to the fact that the market transfers are calendar year contracts rather than monthly. As a result, the ability of the market instruments to meet monthly demand depends largely on how they are allocated throughout the year. In all simulations, the market instruments purchased by the municipalities are allocated in a manner that attempts to maximize the benefit to the municipality. This is done by taking into consideration the total number of monthly failures as well as the magnitude of the shortfalls. More water is allocated at the start of the year to prevent frequent small shortfalls in the earlier months; however, enough water is allocated to the end of the year to limit the occurrence of large shortfalls in November and December. In the liquid market type, spot market leases were used to meet a desired level of reliability. In the other market types, the reliability level of a market portfolio was calculated at the end of the simulation, and the amount of the alternatives were adjusted accordingly. More explanation of simulation details and calculations of reliability can be found in Appendix C.

Another important consideration when creating the simulation model was how to find the optimal level of permanent transfers. Because rights can be bought in perpetuity and the simulations are only one year in duration, a separate decision for finding the optimal number of rights was required. To solve for the optimal number of rights, the simulation was run at the historical average January well height of 670'. This is the expected value of the January well height, and therefore, on average, this is the annual situation that the municipalities will face. Through repeated simulations at this well height, it was determined that 34,000 AF is the optimum level of rights to buy. This decision was based on current municipal demand; however, as municipal demand increases, the model can be changed to find the optimal number of rights in future years. More explanation and results regarding finding the optimal number of rights are located in Appendix D.

The following sections begin by evaluating a market that uses only permanent transfers. Then, additional market instruments are introduced into the market, and the combination of alternatives that minimizes cost while meeting 99% monthly reliability is determined through simulation. Also, the pros and cons of each market type are discussed to help decide which market arrangement is best suited for the Edwards Aquifer.

4.1 Current EA Water Market- Utilizing Annual Leases

SAWS plans to acquire up to 50,000 AF of additional EA water rights through purchases or annual leases from irrigators west of San Antonio (SAWS 2000). In 2001, SAWS purchased 10,400 AF of rights and 9,000 AF of 5-year leases (Water Strategist 2001). By utilizing only permanent and multi-year transfers, SAWS cannot take advantage of current information regarding J17 well levels or changes in demand. Single-year leases are available on the market, but not used very frequently. If single-year leases were utilized, the January J17 well level would be known at the time of purchases. This may reduce the quantity of rights that SAWS and other municipalities need to acquire. Once municipalities buy, they rarely lease back to other sectors. Therefore, if the municipality purchases rights to meet demand in dry years, the water sits idle in the non-dry years, causing a net economic loss to the region.

Figure 4.1 displays the results of running the market simulation to find the quantity of rights needed to meet 99% monthly reliability for a market with only permanent transfers versus one that includes single-year leases.

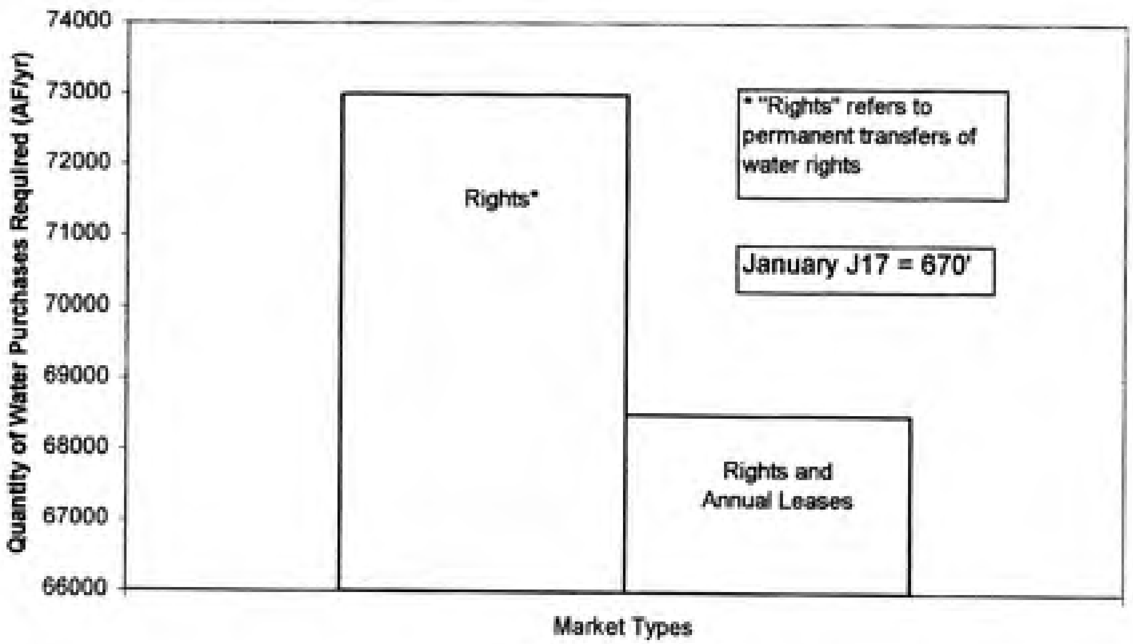

Figure 4.1: Water Required To Meet 99% Reliability vs. Market Alternatives

If buying rights and multi-year transfers are the only available alternatives, knowing the January well height in the first year does not provide any benefit. Regardless of the current well height, the municipality will have to buy rights based on the historic January well height distribution. Therefore, in the "rights only" (hereafter identified as the "rights market") market simulations, the January starting well level was replaced with its historical-based probability distribution. However, if annual leases are utilized, the starting well level is known and can be used to decide how many leases to purchase. The quantity of purchases for the "rights and annual leases" market (hereafter identified as the "annual leases market") shown in Figure 4.1 was calculated for a year that began at the historical average January well height. Note, even when using the average starting well level, having the ability to purchase annual leases as well as rights reduces the amount of water needed to meet 99% reliability by about 4500 AF.

If the January well height in a given year is above average, then the use of annual leases increases the water savings in that year by even more, and conversely, when the starting well level is below average, the savings are not as large. Table 4.1 compares the results for the rights market to the annual leases market at a high, medium, and average well levels. The chosen well levels that correspond to the 10th, 50th, and 90th percentile on the January J17 well level's cumulative distribution function.

Table 4.1: Cost to Meet 99% Monthly Reliability vs. Well Level and Market Type

J17 Jan (ft)	Rights (AF)	Annual Leases (AF)	**Total (AF)**	**Est. Cost Mil. ($/yr)**
685	73000	--	**73000 ± 200**	**3.95 ± 0.02**
	34000	33500	**67500 ± 300**	**3.11 ± 0.03**
670	73000	--	**73000 ± 200**	**3.95 ± 0.02**
	34000	34500	**68500 ± 400**	**3.23 ± 0.04**
650	73000	--	**73000 ± 200**	**3.95 ± 0.02**
	34000	37000	**71000 ± 400**	**3.41 ± 0.04**

The variation in the total number of purchases needed to meet 99% monthly reliability is due somewhat to uncertainty in recharge and discharge, but mostly the variation is due to how the purchases are allocated throughout the year. Example results from numerous simulations of these market types are located in Appendix C.

The estimated cost savings of utilizing annual leases ranges from $500,000 to $800,000 per year, but ultimately these savings depend on the prices adopted in the EA. All of the cost estimates presented herein are calculated using prices derived from the demand curves, as explained in Chapter 3. The variation in cost shown in Table 4.1 is a function of the uncertainty in the quantity needed to meet 99% monthly reliability.

Annual leases and permanent transfers are alternatives currently used in the EA. Thus, the rights and annual leases market is one that could easily be adopted and used by municipalities in the EA. The results indicate that if municipalities were to make more use of annual leases, they would benefit themselves along with the region. The expected benefit from using annual leases would be significant, but not as large as other market types, because the well level in January provides a limited amount of information regarding expected summer shortfalls. If market decisions could be delayed until the summer, the reduction in purchases should be even greater. The following section addresses that assumption by analyzing the benefit of including options as a market alternative.

4.2 Contingent Transfers- Adding Options to the Water Market

By adding contingent transfers to the set of market alternatives, municipalities will have a way to increase their reliability of meeting demand without having to pay the full price of permanent or multi-year transfers. If in June the J17 well is still at a high level, and the municipalities have plenty of water remaining, then the options bought in January will not need to be exercised. Assuming the option price is less than the annual lease price, this would save the municipalities money and require less water to be transferred from agriculture. Figure 4.2 shows how the quantity of water required to meet 99% reliability changes when options are added to the market (identified hereafter as the "options market").

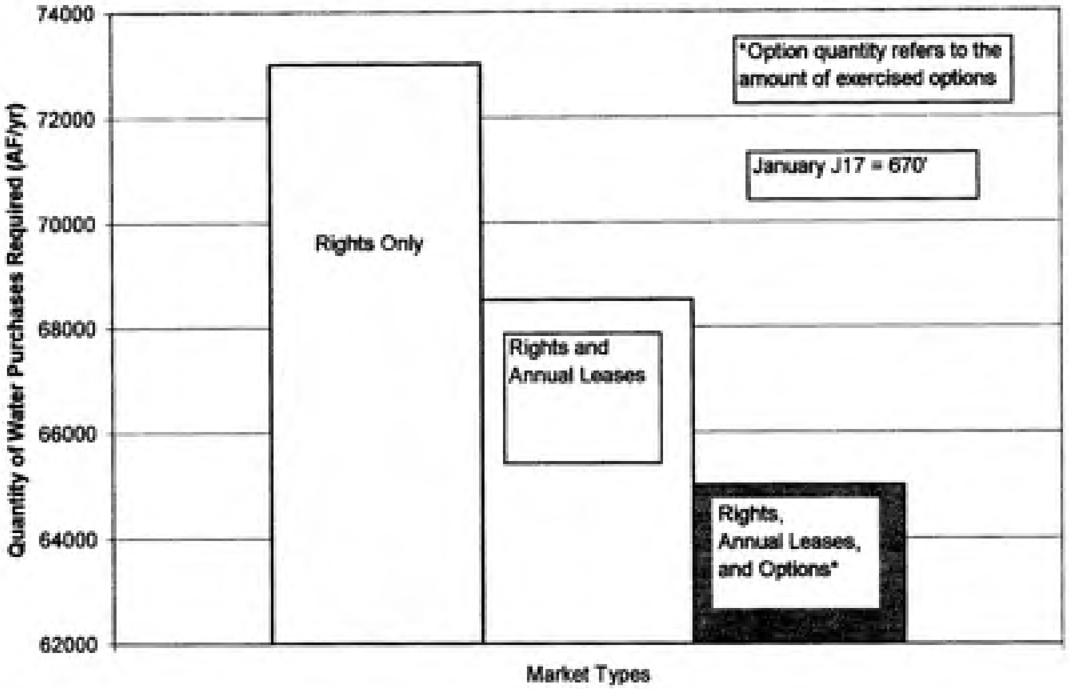

Figure 4.2: Water Required To Meet 99% Monthly Reliability vs. Market Alternatives

Like annual leases, the decision of how many options to buy occurs at the start of the year when the only information known is the January J17 well level. Therefore, the sum of annual leases and options in this market is nearly the same as the quantity of annual leases purchased in the annual leases market. However, because the exercise decision happens later in the year, improved information result about the quantity of rights needed to meet 99% reliability is known. As a result, the average amount of options exercised is about 3000 AF less than the number of options bought. Thus, the market with options requires ~ 3000 AF less water than the annual leases market and 7500 AF less than the rights market. Table 4.2 compares the three market types discussed thus far and shows the optimal number of each market alternative for the various market types.

Table 4.2: Cost to Meet 99% Reliability for Various Well Levels and Market Types

J17 Jan (ft)	Rights (AF)	Annual Leases (AF)	Options (AF)	Ave. Exercised (AF)	Total (AF)	Est. Cost Mil. ($/yr)
685	73000	--	--	--	**73000 ± 200**	**3.95 ± 0.02**
	34000	33500	--	--	**67500 ± 300**	**3.11 ± 0.03**
	34000	14400	19000	16500	**64900± 800**	**2.97± 0.05**
670	73000	--	--	--	**73000 ± 200**	**3.95 ± 0.02**
	34000	34500	--	--	**68500 ± 400**	**3.23 ± 0.04**
	34000	14600	19500	16800	**65400 ± 800**	**3.04± 0.06**
650	73000	--	--	--	**73000 ± 200**	**3.95 ± 0.02**
	34000	37000	--	--	**71000 ± 400**	**3.41 ± 0.04**
	34000	15500	20500	18500	**68000± 800**	**3.18 ± 0.04**

As shown in Table 4.2, the addition of options significantly reduces the quantity needed to meet demand and lowers the expected water supply costs by approximately $900,000 relative to the rights and long-term leases market currently being used in the EA. The ranges of option costs in the last column of Table 4.2 indicate the standard deviation from 1000 simulations runs at the optimal portfolio. Despite the fact that the number of exercised options varies based on the conditions in June, the standard deviation in cost is still less than 2%. The ability of options to meet high levels of reliability while maintaining low average costs and small fluctuations in cost make them desirable to municipalities.

The addition of options in the EA market has been considered and suggested in previous studies of the Edwards (Watkins and McKinney 1999; Keplinger and McCarl 2000). One difficulty in using options is pricing them accurately. The options used in these simulations had an option price of $20/AF and an exercise price of $45-50/AF. The total cost of the option is based on the spot lease price volatility and financial theory, as described in Chapter 3. How the total cost of the option is split between the option and exercise price is typically up to the preferences of the market users. In this project, an option price ($20/AF) was chosen that was high enough to entice farmers to enter into an option contract, but low enough that municipalities could receive a considerable benefit from not exercising the options. In comparison, the annual lease prices in the market simulations were around $50/AF, which is $15-20 less than the total cost of the options. Despite the higher cost, the use of options still resulted in substantial decreases in average costs and quantities, while also eliminating the uncertainty of having to face extremely high spot market prices that might arise during dry years. The inherent uncertainty of the liquid market, presented in the next section, may lead to the options market being the one that finds favor with the municipalities.

4.3 "Liquid" Market- Adding Spot Leases to the Water Market

A liquid market is one in which large quantities of the commodity can be traded quickly and easily. The ease of the transaction encourages more people to use the market and reduces transaction costs. To make the EA market more liquid, spot market leases are added to the simulated market. Spot market leases can take place at any time during the year and last from the time of the transaction until the end of the calendar year. Figure 4.3 displays how the average quantity of water purchases necessary to meet 99% monthly reliability decreases as the short-term alternative of spot leasing is provided as an additional market alternative.

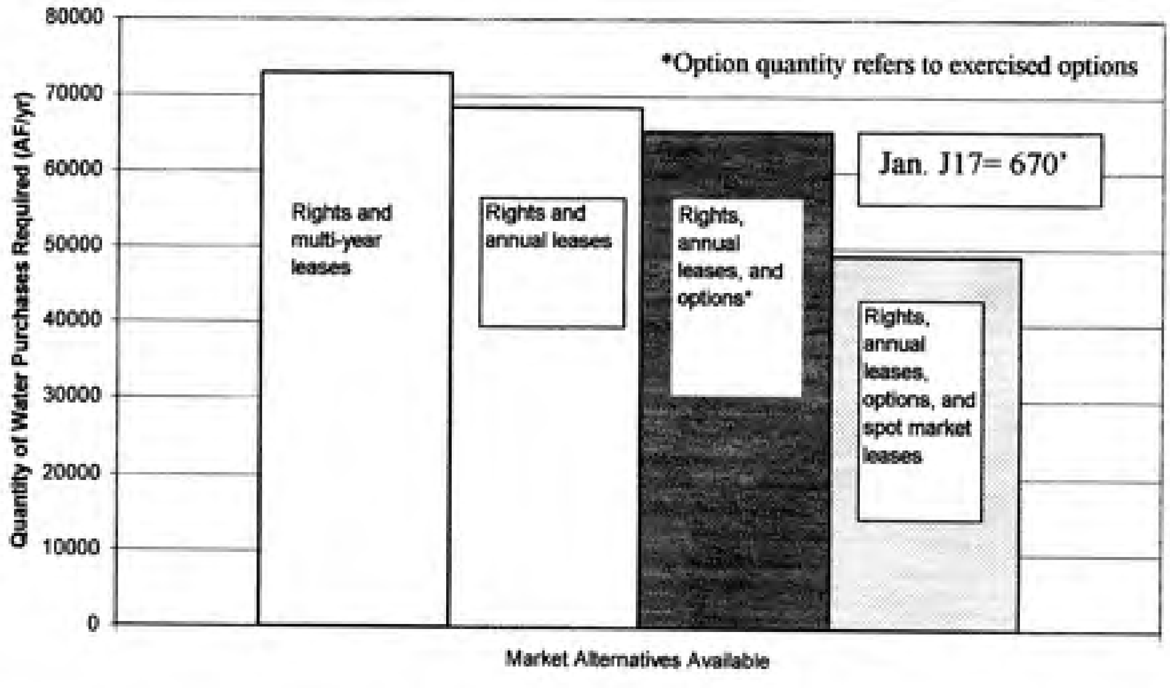

Figure 4.3: Water Required To Meet 99% Monthly Reliability vs. Market Alternatives

The inclusion of spot market leases results in a decrease of over 20,000 AF, down to the average municipal shortfall, as one would expect in a liquid market. The ability to lease based on immediate need allows the municipality to wait until a shortfall is imminent before purchasing additional rights. This significant reduction in water quantity should delay the need for capital expansion projects and reduce the cost of meeting short-term demand. The 49,000 AF of water acquired in the liquid market consists of the optimal mixture of rights, annual leases, options, and spot market leases found by averaging the results of several runs of the simulation program. The results of one such run of the program at 99% reliability and a starting well level of 670' are presented in Figure 4.4.

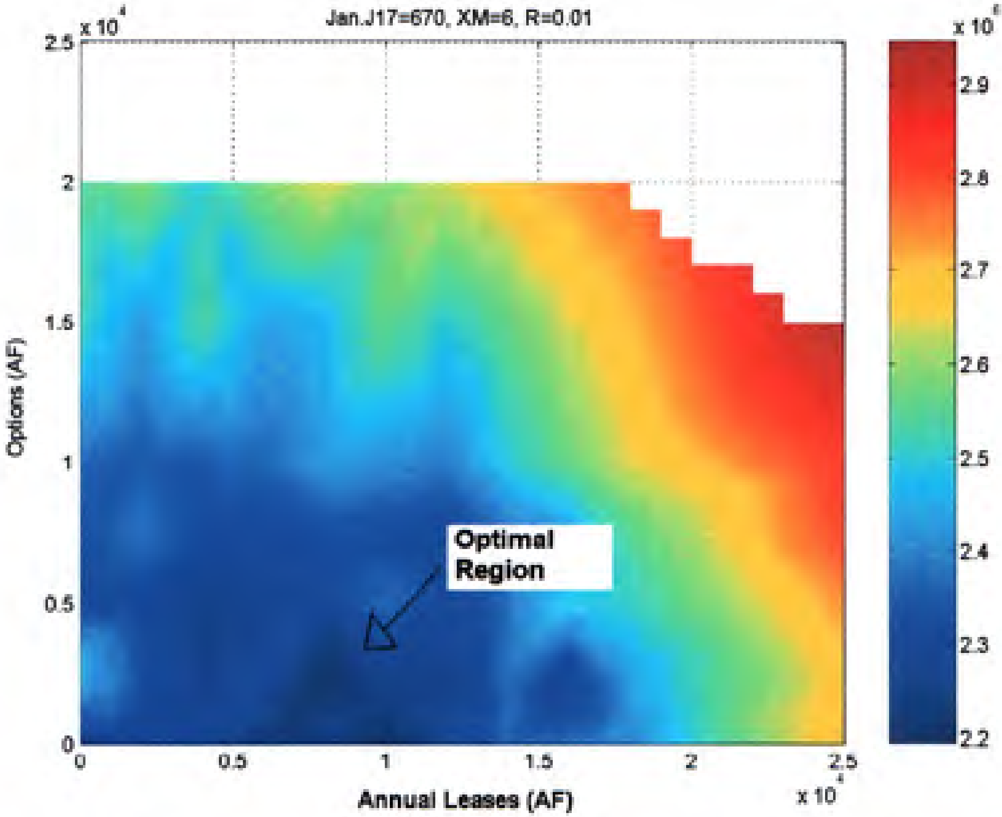

Figure 4.4: Optimizing Water Purchases: Jan. J17= 670', Reliability = 99%

The color bar to the right of Figure 4.4 indicates the cost ($/yr) of meeting demand for the particular combination of options and annual leases. The simulation finds the number of annual leases, options, and spot leases that minimize the average cost of meeting demand (the number of rights is set prior to the simulation at the pre-determined optimal level of 34,000 AF). Figure 4.4 indicates that the optimal market portfolio for a starting well level of 670' is 34,000 AF of rights, 8000 AF of annual leases, and 2500 AF of options. Along with these purchases, on average, another 5000 AF of spot market leases are bought to maintain 99% monthly reliability. So the total amount of water purchased is approximately 49,000 AF, the same as shown in Figure 4.3.

The cost of rights, annual leases, options, and spot market leases in the optimal portfolio are summed to find the total cost of meeting the selected level of reliability. Because of the highly stochastic nature of the problem and the small differences between some portfolios, the cost differences that occur between similar portfolios can be small. Therefore, the simulation model was run repeatedly and the optimum portfolio found several times to observe how the portfolio arrangement changes with each run of the program (See Appendix D for examples of optimization results and changes in optimal portfolios). The liquid market results in Table 4.3 are the average of the optimal portfolios found from running the simulation model numerous times.

Table 4.3: Optimal Water Acquisition vs. Starting Well Height at 99% Reliability

J17 Jan (ft)	Rights	Annual Leases	Options	Average Exercised	Ave. Spot Leases	Total (AF/yr)		Est. Cost (Mil. $/yr)	
						Mean	St. Dev	**Mean**	St. Dev.
685	73000	--	--	--	--	**73000**	200	**3.95**	0.02
	34000	33500	--	--	--	**67500**	300	**3.11**	0.03
	34000	14400	19000	16500	--	**64900**	800	**2.97**	0.05
	34000	6400	600	300	7800	**48500**	9000	**2.17**	1.2
670	73000	--	--	--	--	**73000**	200	**3.95**	0.02
	34000	34500	--	--	--	**68500**	400	**3.23**	0.04
	34000	14600	19500	16800	--	**65400**	800	**3.04**	0.06
	34000	8000	1600	600	6600	**49200**	9500	**2.2**	1.2
650	73000	--	--	--	--	**73000**	200	**3.95**	0.02
	34000	37000	--	--	--	**71000**	400	**3.41**	0.04
	34000	15500	20500	18500	--	**68000**	800	**3.18**	0.04
	34000	8400	1600	600	7400	**50400**	10500	**3.15**	1.3

Although the liquid market results presented in Table 4.3 provide a good indication of the amount of each alternative needed to meet 99% reliability, it may be more practical and useful to present the range of each alternative that can result in a minimum cost. Table 4.4 portrays the optimal range of each temporary transfer alternative. Although the number of each alternative varies slightly, the total number of temporary transfers has a standard deviation of only ~ 4%.

Table 4.4: Optimal Range of Each Temporary Market Alternative

	Temporary Transfers (AF/yr)			
Jan. J17 Well Level (ft)	Range of Annual Leases	Range of Options	Average Amount Spot Leased	Ave. # of Temp. Purchases (AF)
685	4000-8000	0-2500	5000-9000	14500
670	6000-10000	0-2500	5000-9000	15200
650	6000-10000	0-4000	6000-9000	16400

The results presented in Table 4.4 depict the range of each alternative necessary to meet the 99% monthly reliability at the lowest cost. The range of options is low due to the ability to spot lease in conjunction with the relatively high option prices. Option prices are high relative to the average summer spot lease prices due to the high variability in spot lease price. The drawback to spot market leases is that in dry years, it is very likely that the spot market costs will be much more expensive than exercise costs. As a result, in some individual years, the cost of using spot leases to meet demand can be much more expensive. During the 500+ simulation runs for a particular portfolio, the number of spot leases varies considerably to meet reliability. The quantities of spot leases in Table 4.3 and 4.4 refer to the average amount spot leased over the 500+ recharge and discharge events. The standard deviation in spot leases is about 9000 AF. This is much higher than the variation of exercised options in the options market. As a result, the standard deviation in cost on the liquid market is much higher ($1.2 million/yr) than it is on the options market ($50,000/yr). The ability of options to reduce annual cost fluctuations may make this market more appealing to the municipality. Regardless of which market is chosen for the EA, it is clear from the above results that the addition of options and spot market leases significantly reduces water supply quantities and costs needed to meet 99% reliability.

4.5 Cost vs. Reliability

Reliability is a major concern of municipalities when using a market to meet demand. Ownership of a plentiful water source increases the municipalities' confidence that they can meet demand, but ownership comes at a premium price. Figure 4.6 displays how costs change with the monthly reliability level. Monthly rather than annual reliability was selected because when the well level drops below 650' the municipality's *monthly* use is restricted, and it must turn to the market to meet demand. The IRP's currently owned by the municipality and the rights bought in the simulation were distributed monthly so that monthly failures occurred at approximately the same percentage in any month. A 99% monthly reliability is approximately equivalent to failing to meet demand in one month during an 8 year time period.

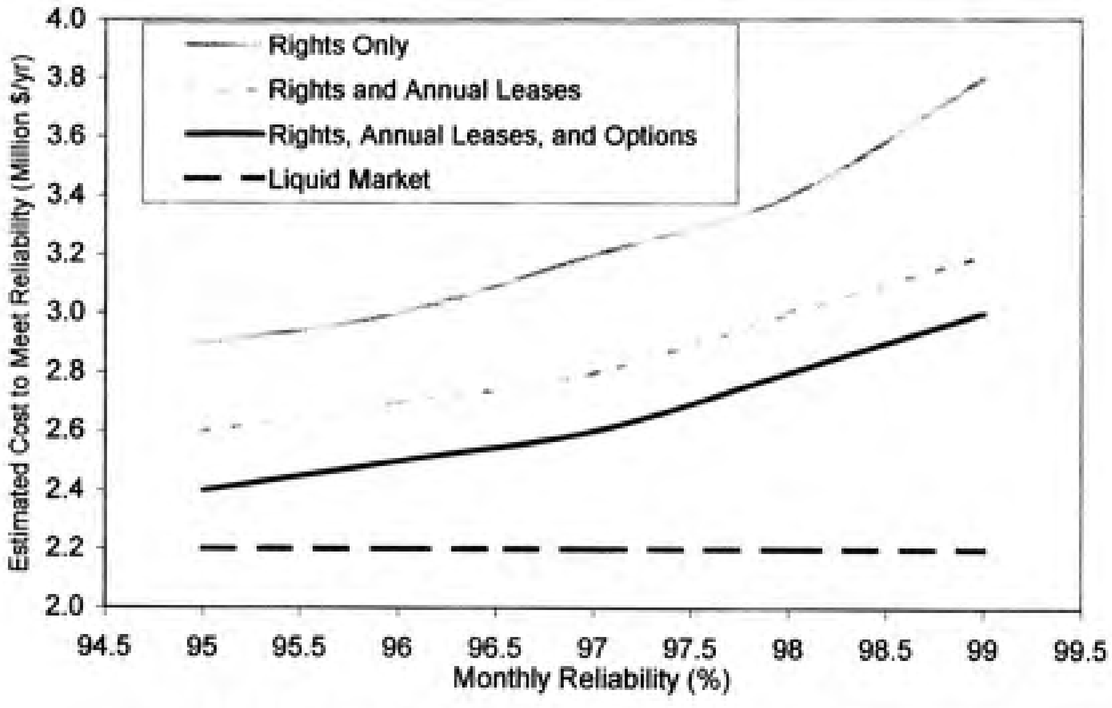

Figure 4.5: Cost vs. Reliability: January Well Height at Average (670')

Rights, annual leases, and options are all purchases that happen at the start of the year. Therefore increasing reliability means buying more water because no new information is available at the start of the year. This causes the costs for the three top curves in Figure 4.5 to increase with reliability. Waiting until June to decide whether or not to exercise the options, makes it a cheaper alternative than the rights market and the annual leases market. However, costs still increase with reliability because the number of options must be purchased upfront. In all simulations, the option price was $20/AF and the exercise price was between 45-50 $/AF. The increase of cost with reliability in the options market will vary somewhat depending on the combination of option/exercise price that is selected.

In the liquid market, the average cost of meeting demand does not change noticeably with monthly reliability. The curve in Figure 4.5 representing the liquid market type stays approximately constant at $2.2 million per year even as reliability increases. This is because the spot leases allow the municipality to wait until a shortfall is upon them before buying more water. Averaged out over hundreds of simulation runs, the small spot lease purchases used to meet reliability do not significantly increase the expected cost. Therefore, if the market was run efficiently, the municipalities could be assured of any given reliability level at a much lower cost than if owning the water were the only alternative. Thus, not only does the liquid market reduce the amount of purchases necessary, consequently reducing the cost of meeting demand, but it also enables municipalities to meet any level of reliability with little cost changes. However, a liquid market has a much higher standard deviation of cost and also places the municipalities at the mercy of the farmers during shortfalls. As a result, the options market may be selected over the liquid market. As indicated in Figure 4.5, this market type also significantly reduces the cost of meeting reliability. Whichever market is chosen, it is clear from these results that the inclusion of temporary and contingent transfers in the EA market can assist in reducing the cost and number of transfers needed to meet municipal demand.

5. CONCLUSIONS

The goal of this project is to provide a decision-making framework for municipalities that reduces the cost of meeting demand and delays the need for capital projects that will deplete other water sources. The simulation model developed in this project utilizes Monte Carlo sampling from discharge and recharge distributions to predict well levels and water demand in the Edwards Aquifer. This stochastic approach to water supply and demand, in conjunction with economic information derived from municipal and agricultural demand curves, allows us to simulate market activity in the Edwards. The simulation tries hundreds of combinations of market alternatives (rights, annual leases, options, and spot market leases) to find the portfolio that minimizes the expected cost of meeting demand when averaged over hundreds of possible recharge and discharge scenarios. The results from the optimization through simulation approach developed in this project have potentially valuable applications in the region.

First, our analysis indicates that through proper utilization of the existing water market, municipalities in the Edwards can meet their present demands with at least 99% monthly reliability. By trading water rights to the highest valued use, there is a net regional benefit, and municipalities are able to utilize the much cheaper alternative of purchasing EA rights to delay the need for the capital-intensive water supply projects under consideration. The water market that ultimately develops in this region may take on several forms. This project studied four methods of market transfers: buying rights (permanent transfers), annual leases, options, and spot market leases; and simulated activity on four potential market types to evaluate their ability to meet municipal demand. The four market types considered are: (1) Rights only, (2) Rights and Annual Leases, (3) Rights, Annual Leases, and Options, and (4) Liquid Market: Rights, Annual Leases, Options, and Spot Market Leases.

Although annual leases are currently available on the EA market, they are not used to the degree that multi-year leases and permanent transfers are. Because municipal permits can be cutback when the aquifer level is low, knowing the well height in January provides information about potential municipal shortfalls. Consequently, simulation results indicate that by increasing the use of annual leases, rather than permanent transfers, municipalities can reduce the quantity of water needed to meet 99% monthly reliability by about 5000 AF/yr (1.7 billion gallons/yr). This reduction in water quantity should lead to significant cost savings.

Next, the new market alternatives, options and spot market leases, are added to the simulations and evaluated. By delaying market decisions until more information regarding well levels and demand is known, these alternatives further reduce the quantity of water necessary to meet any level of reliability. The addition of spot market leases results in the most significant reduction in water quantity of the four market types studied. The ability to spot lease to meet immediate demands allows the municipality to attain increasing levels of reliability without a noticeable increase in costs. However, the use of spot market leases results in the highest standard deviation in quantity of water purchases needed to meet demand and consequently, the highest standard deviation in costs. In dry years, the heavy reliance on spot market leases will cause the liquid market type to be more costly than market types 2 and 3. The use of options rather than spot market leases decreases costs, without the large standard deviation in costs experienced in the liquid market. The use of options rather than spot leases also prevents the municipality from having to obtain water at the last minute; in which case, they will be at the mercy of the agricultural users in the region to meet demand. Although each potential market type has pros and cons, it is evident from the simulation results that contingent (options) and temporary (annual and spot leases) transfers can lead to a substantial reduction in the quantity and costs needed to meet a desired level of reliability.

Lastly, unlike previous studies, option pricing in this project is addressed in a rigorous manner consistent with option pricing theory. Simulating market activity enables the development of monthly spot market lease price distributions. These distributions allow us to utilize the expected lease prices and lease price volatility to compute option and exercise prices in accordance with financial theory. Although June was selected as the exercise month is this project, the decision analysis for pricing, buying, and exercising options for any option and exercise arrangement are described in this work.

Recommendations for Future Work

Because options and spot market leases are not currently used on the market, pricing had to be simulated by estimating agricultural and municipal demand curves and using economic theory of supply and demand. The uncertainty in monthly prices was primarily a function of uncertainty in recharge and discharge. Added uncertainty could be incorporated directly into the pricing formulas to reflect the deviations from ideal economic behavior that is likely to occur. As the market is used more frequently and efficiently, actual pricing data will become available that will allow us to evaluate the assumptions of market behavior made in this model. Two important assumptions to reassess are the agricultural elasticities and the lease price variation constraints.

The simulation model employed in this work is a single-year model. The creation of a multi-year model in which demand increases over time will improve the ability to determine the advantages of permanent water transfers and of using the market to meet future needs.

An important conclusion of this work is that options and spot leases reduce the average quantity and cost required to meet demand. Spot market leases result in the lowest average cost but have the highest standard deviation in cost. Options do not result in as much of an average cost reduction, but involve much less cost fluctuations. An assessment of the municipalities' risk preferences will enable us to better which market alternative or combination of alternatives is most desirable to municipalities.

Addendum

In conclusion, the results presented in this work support the position that the use of contingent and short-term market transfers leads to a substantial reduction in the water quantity and cost necessary to meet demand. Moreover, the benefits of an efficient market are likely to be even more pronounced now that the new drought management rules have been put into place. The revised rules, released May 2002, include a new cutback of 30% when the well level drops below 627' and increase the previous cutback levels by an additional 5% (i.e.- a cutback of 10% when J17 well drops below 650'). The results of running the market simulations under the new restrictions are shown in Figure 5.1.

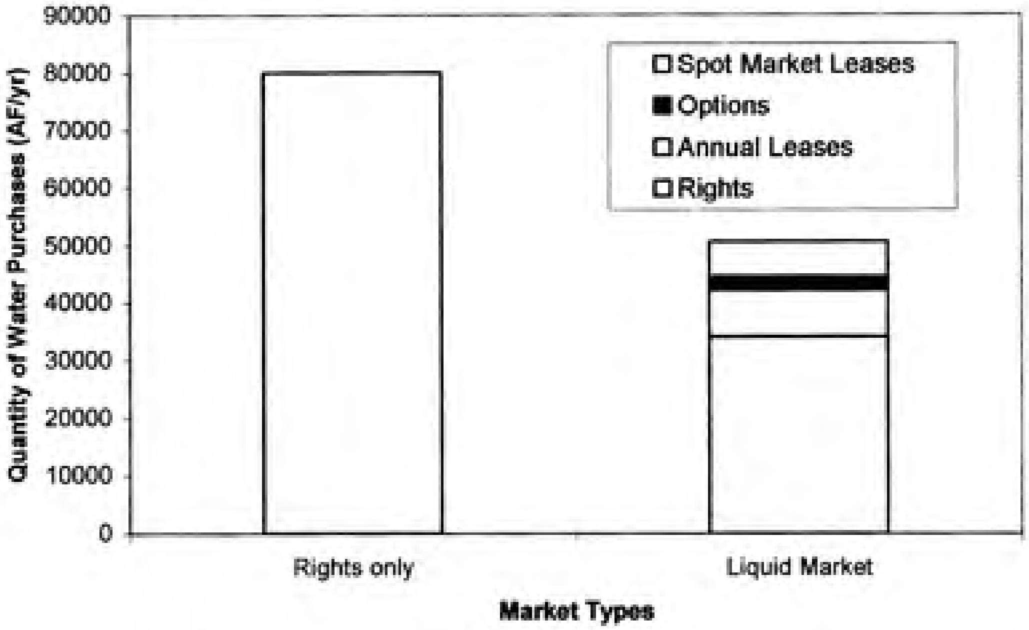

Figure 5.1: Meeting 99% Monthly Reliability Under the New Restrictions

The changes in cutbacks cause the number of rights necessary to meet 99% reliability to increase from 73,000 to 80,000 AF. Without the availability of short-term or contingent transfers, the municipalities have to prepare for these cutbacks by buying more rights. The number of spot leases in the Figure 5.1 represents the average amount necessary to meet reliability over the 500+ simulation runs. Although, the spot leases may increase in one or two years to meet the new restrictions, which could be very expensive, on average there is very little change in the annual amount necessary. As a result, the number of purchases in the liquid market remains near 49,000 AF, the same as under the old restrictions. The total reduction in quantity of purchases from the "rights only" market to the liquid market is around 30,000 AF/yr. Thirty-thousand acre-feet is approximately 10 billion gallons. This is a considerable reduction in water supply development needs. With the rapidly depleting availability of ground and surface water sources, the potential water (and cost) savings that result from improved allocation through water marketing must be considered in the Edwards and other regions as a viable alternative to meet demand.

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Appendix A
Discharge and Recharge Data

A.1) Discharge by Use in the Edwards Aquifer
A.2) Edwards Recharge Data
A.3) Inflow, Agricultural and Municipal Discharge Distributions

A.1) Estimated Discharge by Use in the Edwards Aquifer

Year	Irrigation	Domestic/ Municipal	Stock	Industrial/ Commercial	Springs
1955	85.2	120.5	30.1	25.1	127.8
1956	127.2	138.3	28.9	22.4	69.8
1957	68.8	116.1	29.8	22.6	219.2
1958	47.2	113.7	33.4	25.1	398.2
1959	60	118.9	31.5	24.2	384.5
1960	54.9	121.1	29.1	23.3	428.3
1961	52.1	124.5	29.6	22.2	455.3
1962	72.7	143.7	28.8	22.8	321.1
1963	75.4	151.8	27.8	21.8	239.6
1964	72.6	140.2	26.3	21.7	213.8
1965	68	138.8	27	22.3	322.8
1966	68.2	141.8	23.3	22.6	315.3
1967	119.4	171	25.1	25.8	216.1
1968	59.3	146.9	25.5	20	408.3
1969	95.2	162	29.2	21.1	351.2
1970	110.1	167.5	29.3	22.5	397.7
1971	159.4	196.2	28.6	22.6	272.7
1972	128.8	190.5	30.8	21.1	375.8
1973	82.2	177.1	32.3	18.8	527.6
1974	140.4	174.6	33.5	15.1	483.3
1975	96.4	182.5	33.6	15.3	540.4
1976	118.2	182.1	34.6	14.7	503.9
1977	124.2	205.3	38.1	13	580.3
1978	165.8	214.2	40.3	11.5	375.5
1979	126.8	208.9	40.7	15.2	523
1980	177.9	256.2	43.3	13.7	328.3
1981	101.8	231.8	40.9	12.6	407.3
1982	130	268.6	39.5	15	333.3
1983	115.9	249.2	38.8	14.7	301.5
1984	191.2	287.2	36.2	15.2	178.3
1985	203.1	263.7	39.2	16.5	334
1986	104.2	266.3	42	16.8	388
1987	40.9	260.9	43.5	18.7	557.9
1988	193.1	286.2	41.9	18.8	369.7
1989	196.2	285.2	38.2	22.9	224.1
1990	172.9	254.9	37.9	23.7	240.6
1991	88.5	240.5	39.5	67.5	354.6
1992	27.1	236.5	34.8	29	802.8
1993	69.3	252	49.9	36.1	589.4
1994	104.5	247	33.9	39.3	390.2
1995	95.6	255	*11.6	37.3	361.3
1996	181.3	261.3	*12.3	38.8	212
1997	77.4 a/b	253	12.3	34.4	383.9

1998	131.9 a	266.5	13.4	41.7 b	464.1
Average 1955-98	108.7	201.6	32.2	23.3	369.8
Median 1955-98	103	200.7	32.9	22.2	372.6
Average 1988-98	114.5	255.2	28.4	37.1	402.1
Median 1988-98	100.1	254	34.4	36.7	372.6

Data source: USGS and Edwards Aquifer Authority, 1999.

"a" Includes estimates from Atascosa County discharge by Edwards Aquifer users.

"b" Includes estimates from Guadalupe County discharge by Edwards Aquifer users.

Differences may occur due to rounding procedures.

*In 1995 the USGS revised the method of calculating domestic/livestock pumpage, which significantly decreased the estimate for 1995 and 1996.

A.2) Estimated Recharge in the Edwards

Data in 1000s of AF

Year	Nueces River-West Nueces River basin	Frio River-Dry Frio River basin	Sabinal River basin	Area between Sabinal River and Medina River basin	Medina River basin	Area between Medina River and Cibolo Creek- Dry Comal Creek basin	Cibolo Creek - Dry Comal Creek basin	Blanco River basin	'Total
1934	8.6	27.9	7.5	19.9	46.5	21	28.4	19.8	179.6
1935	411.3	192.3	56.6	166.2	71.1	138.2	182.7	39.8	1258.2
1936	176.5	157.4	43.5	142.9	91.6	108.9	146.1	42.7	909.6
1937	28.8	75.7	21.5	61.3	80.5	47.8	63.9	21.2	400.7
1938	63.5	69.3	20.9	54.1	65.5	46.2	76.8	36.4	432.7
1939	227	49.5	17	33.1	42.4	9.3	9.6	11.1	399
1940	50.4	60.3	23.8	56.6	38.8	29.3	30.8	18.8	308.8
1941	89.9	151.8	50.6	139	54.1	116.3	191.2	57.8	850.7
1942	103.5	95.1	34	84.4	51.7	66.9	93.6	28.6	557.8
1943	36.5	42.3	11.1	33.8	41.5	29.5	58.3	20.1	273.1
1944	64.1	76	24.8	74.3	50.5	72.5	152.5	46.2	560.9
1945	47.3	71.1	30.8	78.6	54.8	79.6	129.9	35.7	527.8
1946	80.9	54.2	16.5	52	51.4	105.1	155.3	40.7	556.1
1947	72.4	77.7	16.7	45.2	44	55.5	79.5	31.6	422.6
1948	41.1	25.6	26	20.2	14.8	17.5	19.9	13.2	178.3
1949	166	66.1	31.5	70.3	33	41.8	55.9	23.5	508.1
1950	41.5	35.5	13.3	27	23.6	17.3	24.6	17.4	200.2
1951	18.3	28.4	7.3	26.4	21.1	15.3	12.5	10.6	139.9
1952	27.9	15.7	3.2	30.2	25.4	50.1	102.3	20.7	275.5
1953	21.4	15.1	3.2	4.4	36.2	20.1	42.3	24.9	167.6
1954	61.3	31.6	7.1	11.9	25.3	4.2	10	10.7	162.1
1955	128	22.1	0.6	7.7	16.5	4.3	3.3	9.5	192
1956	15.6	4.2	1.6	3.6	6.3	2	2.2	8.2	43.7
1957	108.6	133.6	65.4	129.5	55.6	175.6	397.9	76.4	1142.6
1958	266.7	300	223.8	294.9	95.5	190.9	268.7	70.7	1711.2
1959	109.6	158.9	61.6	96.7	94.7	57.4	77.9	33.6	690.4
1960	88.7	128.1	64.9	127	104	89.7	160	62.4	824.8
1961	86.2	161.3	57.4	105.4	88.3	69.3	110.8	49.4	717.1
1962	47.4	46.6	4.3	23.5	57.3	16.7	24.7	18.9	239.4
1963	39.7	27	5	10.3	41.9	9.3	21.3	16.2	170.7
1964	126.1	57.1	16.3	61.3	43.3	35.8	51.1	22.2	413.2
1965	97.9	83	23.2	104	54.6	78.8	115.3	66.7	623.5
1966	169.2	134	37.7	78.2	50.5	44.5	66.5	34.6	615.2
1967	82.2	137.9	30.4	64.8	44.7	30.2	57.3	19	466.5
1968	130.8	176	66.4	198.7	59.9	83.1	120.5	49.3	884.7
1969	119.7	113.8	30.7	84.2	55.4	60.2	99.9	46.6	610.5
1970	112.6	141.9	35.4	81.6	68	68.6	113.8	39.5	661.6
1971	263.4	212.4	39.2	155.6	68.7	81.4	82.4	22.2	925.3
1972	108.4	144.6	49	154.6	87.9	74.3	104.2	33.4	756.4
1973	190.6	256.9	123.9	286.4	97.6	237.2	211.7	82.2	1486.5
1974	91.1	135.7	36.1	115.3	96.2	68.1	76.9	39.1	658.5

1975	71.6	143.6	47.9	195.9	93.4	138.8	195.7	85.9	973
1976	160.7	238.6	68.2	182	94.5	47.9	54.3	57.9	894.1
1977	102.9	193	62.7	159.5	77.7	97.9	191.6	66.7	952
1978	69.8	73.1	30.9	103.7	76.7	49.6	72.4	26.3	502.5
1979	128.4	201.4	68.6	203.1	89.4	85.4	266.3	75.2	1117.8
1980	58.6	85.6	42.6	25.3	88.3	18.8	55.4	31.8	406.4
1981	205	365.2	105.6	252.1	91.3	165	196.8	67.3	1448.3
1982	19.4	123.4	21	90.9	76.8	22.6	44.8	23.5	422.4
1983	79.2	85.9	20.1	42.9	74.4	31.9	62.5	23.2	420.1
1984	32.4	40.4	8.8	18.1	43.9	11.3	16.9	25.9	197.7
1985	105.9	186.9	50.7	148.5	64.7	136.7	259.2	50.7	1003.3
1986	188.4	192.8	42.2	173.6	74.7	170.2	267.4	44.5	1153.8
1987	308.5	473.3	110.7	405.5	90.4	229.3	270.9	114.9	2003.5
1988	59.2	117.9	17	24.9	69.9	12.6	28.5	25.5	355.5
1989	52.6	52.6	8.4	13.5	46.9	4.6	12.3	23.6	214.4
1990	479.3	255	54.6	131.2	54	35.9	71.8	41.3	1123.1
1991	325.2	421	103.1	315.2	52.8	84.5	109.7	96.9	1508.4
1992	234.1	586.9	201.1	566.1	91.4	290.6	286.6	226.9	2486
1993	32.6	78.5	29.6	60.8	78.5	38.9	90.9	37.8	447.6
1994	124.6	151.5	29.5	45.1	61.1	34.1	55.6	36.6	538.1
1995	107.1	147.6	34.7	62.4	61.7	36.2	51.1	30.6	531.3
1996	130	92	11.4	9.4	42.3	10.6	14.7	13.9	324.3
1997	176.9	209.1	57	208.4	63.3	193.4	144.2	82.3	1134.6
1998	141.5	214.8	72.5	201.4	80.3	86.2	240.9	104.7	1142.3

For the period of record 1934-1998:

Average	117	134.4	42.1	108.5	61.4	70.8	106	42.9	683.1
Median	97.9	117.9	30.9	78.6	59.9	50.1	77.9	34.6	556.1

For the period of record 1989-1998:

Average	180.4	220.9	60.2	161.4	63.2	81.5	107.8	69.5	945
Median	135.8	180.3	44.7	96.8	61.4	37.6	81.4	39.6	830.6

Data source: USGS, 1999.

*Total may not be equal to sum of basin values due to rounding.

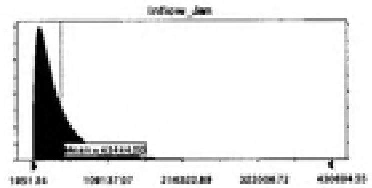
A.3) Monthly Probability Distributions

INFLOW DISTRIBUTIONS

Assumption: Inflow_Jan — **Cell: C21**

Lognormal distribution with parameters:

Mean	43444.00
Standard Dev.	48491.00



Selected range is from 0.00 to +Infinity

Correlated with:

AG_jan (E21)	-0.20
Inflow_Feb (C22)	0.84
MI jan (D21)	-0.15

Assumption: Inflow_Feb — **Cell: C22**

Lognormal distribution with parameters:

Mean	47472.59
Standard Dev.	50817.12

Selected range is from 0.00 to +Infinity

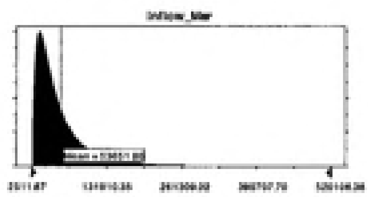
Correlated with:

AG_feb (E22)	-0.35
Inflow_Mar (C23)	0.87
MI feb (D22)	-0.30
Inflow_Jan (C21)	0.84

Assumption: Inflow_Mar — **Cell: C23**

Lognormal distribution with parameters:

Mean	53651.80



Standard Dev. 58858.44

Selected range is from 0.00 to +Infinity

Assumption: Inflow_Mar (cont'd) **Cell: C23**

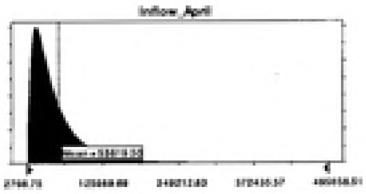
Correlated with:

AG_mar (E23)	-0.45
Inflow_Feb (C22)	0.87
Inflow_April (C24)	0.53
MI mar (D23)	-0.40

Assumption: Inflow_April **Cell: C24**

Lognormal distribution with parameters:

Mean	53819.50
Standard Dev.	56757.42



Selected range is from 0.00 to +Infinity

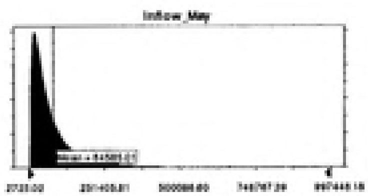
Correlated with:

AG_apr (E24)	-0.60
Inflow_Mar (C23)	0.53
Inflow_May (C25)	0.68
MI apr (D24)	-0.55

Assumption: Inflow_May **Cell: C25**

Lognormal distribution with parameters:

Mean	84585.01
Standard Dev.	108065.28



Selected range is from 0.00 to +Infinity

Correlated with:

Ag_may (E25)	-0.55
Inflow_April (C24)	0.68
Inflow_June (C26)	0.45
MI may (D25)	-0.50

Assumption: Inflow_June **Cell: C26**

Lognormal distribution with parameters:

Mean	91247.00
Standard Dev.	157216.55

Selected range is from 0.00 to +Infinity

Correlated with:

AG_jun (E26)	-0.45
Inflow_May (C25)	0.45
Inflow_July (C27)	0.36
MI jun (D26)	-0.40

Assumption: Inflow_July **Cell: C27**

Lognormal distribution with parameters:

Mean	54617.26
Standard Dev.	75396.73

Selected range is from 0.00 to +Infinity

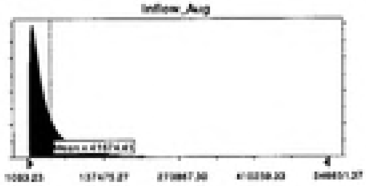
Correlated with:

AG_jul (E27)	-0.55
Inflow_Aug (C28)	0.27
Inflow_June (C26)	0.36
MI july (D27)	-0.50

Assumption: Inflow_Aug — **Cell: C28**

Lognormal distribution with parameters:

Mean	41674.41
Standard Dev.	57940.32



Selected range is from 0.00 to +Infinity

Correlated with:

Inflow_July (C27)	0.27
Inflow_Sept (C29)	0.19
MI aug (D28)	-0.45
AG_aug (E28)	-0.50

Assumption: Inflow_Sept — **Cell: C29**

Lognormal distribution with parameters:

Mean	57934.10
Standard Dev.	81658.57

Selected range is from 0.00 to +Infinity

Correlated with:

AG_sep (E29)	-0.55
Inflow_Aug (C28)	0.19
Inflow_Oct (C30)	0.33
MI sep (D29)	-0.50

Assumption: Inflow_Oct — **Cell: C30**

Lognormal distribution with parameters:

Mean	63212.61
Standard Dev.	87127.42

Selected range is from 0.00 to +Infinity

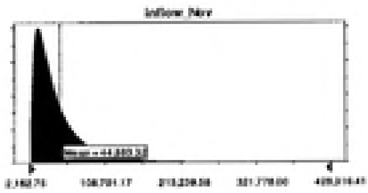
Correlated with:

AG_oct (E30)	-0.45
Inflow_Sept (C29)	0.33
Inflow_Nov (C31)	0.75
MI oct (D30)	-0.40

Assumption: Inflow_Nov — **Cell: C31**

Lognormal distribution with parameters:

Mean	44,883.32
Standard Dev.	48,646.12



Selected range is from 0.00 to +Infinity

Correlated with:

AG_nov (E31)	-0.30
Inflow_Oct (C30)	0.75
Inflow_Dec (C32)	0.36
MI nov (D31)	-0.27

Assumption: Inflow_Dec — **Cell: C32**

Lognormal distribution with parameters:

Mean	46576.36
Standard Dev.	53711.88

Selected range is from 0.00 to +Infinity

Correlated with:

AG_dec (E32)	-0.30
Inflow_Nov (C31)	0.36
MI dec (D32)	-0.25

End of Assumptions

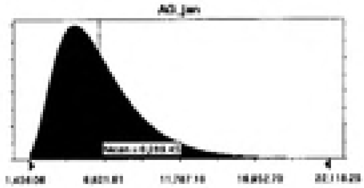
Agricultural Use

Cell: E21

Assumption: AG_jan

Lognormal distribution with parameters:

Mean	6,289.45
Standard Dev.	3,005.00



Selected range is from 0.00 to +Infinity

Correlated with:

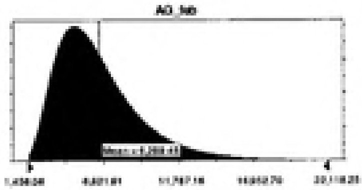
Inflow_Jan (C21)	-0.20
MI jan (D21)	0.50

Assumption: AG_feb

Cell: E22

Lognormal distribution with parameters:

Mean	6,289.45
Standard Dev.	3,005.00



Selected range is from 0.00 to +Infinity

Correlated with:

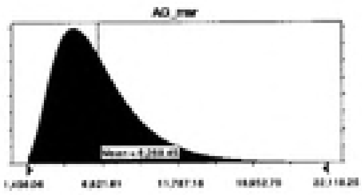
Inflow_Feb (C22)	-0.35
MI feb (D22)	0.55

Assumption: AG_mar

Cell: E23

Lognormal distribution with parameters:

Mean	6,289.45
Standard Dev.	3,005.00



Selected range is from 0.00 to +Infinity

Correlated with:

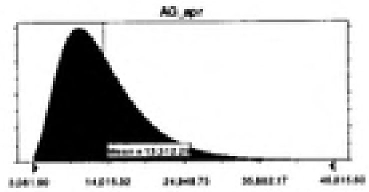
Inflow_Mar (C23)	-0.45
MI mar (D23)	0.45

Cell: E24

Assumption: AG_apr

Lognormal distribution with parameters:

Mean	13,312.29
Standard Dev.	6,360.39



Selected range is from 0.00 to +Infinity

Correlated with:

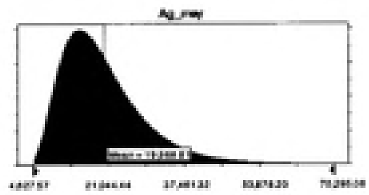
Inflow_April (C24)	-0.60
MI apr (D24)	0.70

Cell: E25

Assumption: Ag_may

Lognormal distribution with parameters:

Mean	19,988.81
Standard Dev.	9,550.32



Selected range is from 0.00 to +Infinity

Correlated with:

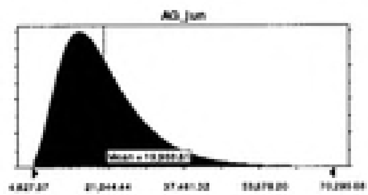
Inflow_May (C25)	-0.55
MI may (D25)	0.70

Cell: E26

Assumption: AG_jun

Lognormal distribution with parameters:

Mean	19,988.81
Standard Dev.	9,550.32



Selected range is from 0.00 to +Infinity

Correlated with:

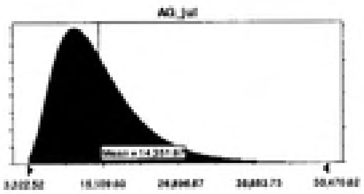
Inflow_June (C26)	-0.45
MI jun (D26)	0.70

Cell: E27

Assumption: AG_jul

Lognormal distribution with parameters:

Mean	14,351.67
Standard Dev.	6,856.99



Selected range is from 0.00 to +Infinity

Correlated with:

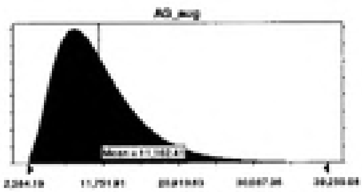
Inflow_July (C27)	-0.55
MI july (D27)	0.30

Cell: E28

Assumption: AG_aug

Lognormal distribution with parameters:

Mean	11,162.41
Standard Dev.	5,333.22



Selected range is from 0.00 to +Infinity

Correlated with:

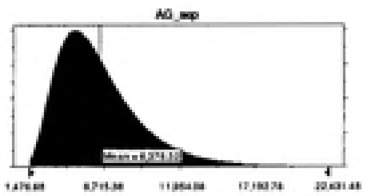
Inflow_Aug (C28)	-0.50
MI aug (D28)	0.15

Cell: E29

Assumption: AG_sep

Lognormal distribution with parameters:

Mean	6,378.52
Standard Dev.	3,047.55



Selected range is from 0.00 to +Infinity

Correlated with:

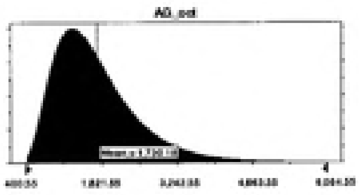
Inflow_Sept (C29)	-0.55
MI sep (D29)	0.20

Cell: E30

Assumption: AG_oct

Lognormal distribution with parameters:

Mean	1,730.18
Standard Dev.	826.65



Selected range is from 0.00 to +Infinity

Correlated with:

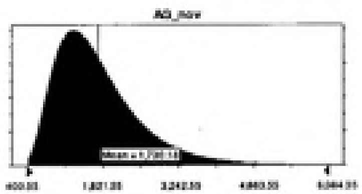
Inflow_Oct (C30)	-0.45
MI oct (D30)	0.10

Cell: E31

Assumption: AG_nov

Lognormal distribution with parameters:

Mean	1,730.18
Standard Dev.	826.65



Selected range is from 0.00 to +Infinity

Correlated with:

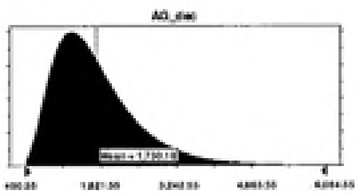
Inflow_Nov (C31)	-0.30
MI nov (D31)	0.30

Cell: E32

Assumption: AG_dec

Lognormal distribution with parameters:

Mean	1,730.18
Standard Dev.	826.65



Selected range is from 0.00 to +Infinity

Correlated with:

Inflow_Dec (C32)	-0.30
MI dec (D32)	0.40

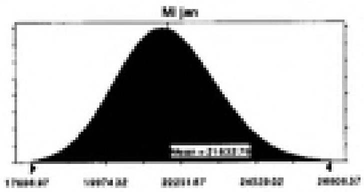
Municipal and Industrial Use

Cell: D21

Assumption: MI jan

Lognormal distribution with parameters:

Mean	21832.76
Standard Dev.	1512.80



Selected range is from 0.00 to +Infinity

Correlated with:

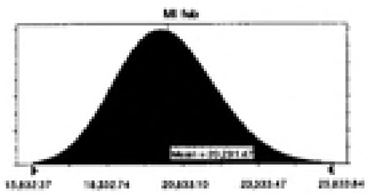
AG_jan (E21)	0.50
Inflow_Jan (C21)	-0.15

Cell: D22

Assumption: MI feb

Lognormal distribution with parameters:

Mean	20,291.47
Standard Dev.	1,658.64



Selected range is from 0.00 to +Infinity

Correlated with:

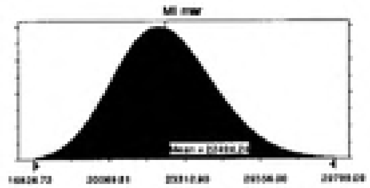
AG_feb (E22)	0.55
Inflow_Feb (C22)	-0.30

Cell:

D23

Assumption: MI mar

Lognormal distribution with parameters:		
Mean	22494.24	
Standard Dev.	2147.48	



Selected range is from 0.00 to +Infinity

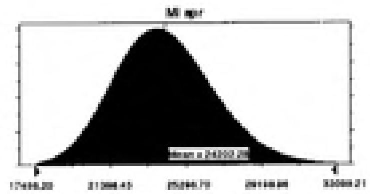
Correlated with:

AG_mar (E23)	0.45
Inflow_Mar (C23)	-0.40

Cell:
D24

Assumption: MI apr

Lognormal distribution with parameters:		
Mean	24202.28	
Standard Dev.	2578.40	



Selected range is from 0.00 to +Infinity

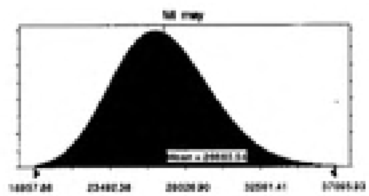
Correlated with:

AG_apr (E24)	0.70
Inflow_April (C24)	-0.55

Cell:
D25

Assumption: MI may

Lognormal distribution with parameters:		
Mean	26685.54	
Standard Dev.	2994.98	



Selected range is from 0.00 to +Infinity

Correlated with:

Ag_may (E25)	0.70
Inflow_May (C25)	-0.50

Cell: D26

Assumption: MI jun

Lognormal distribution with parameters:

Mean	29005.55
Standard Dev.	4386.60

Selected range is from 0.00 to +Infinity

Correlated with:

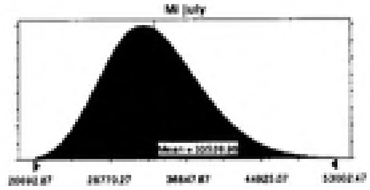
AG_jun (E26)	0.70
Inflow_June (C26)	-0.40

Cell: D27

Assumption: MI july

Lognormal distribution with parameters:

Mean	33526.98
Standard Dev.	5288.08



Selected range is from 0.00 to +Infinity

Correlated with:

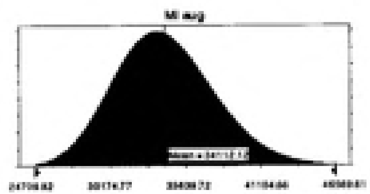
AG_jul (E27)	0.30
Inflow_July (C27)	-0.50

Cell: D28

Assumption: MI aug

Lognormal distribution with parameters:

Mean	34112.12
Standard Dev.	3613.15



Selected range is from 0.00 to +Infinity

Correlated with:

Inflow_Aug (C28)	-0.45

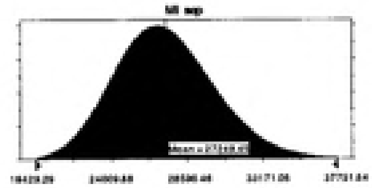
AG_aug (E28) 0.15

Cell:
D29

Assumption: MI sep

Lognormal distribution with parameters:

Mean	27249.45
Standard Dev.	3026.00



Selected range is from 0.00 to +Infinity

Correlated with:

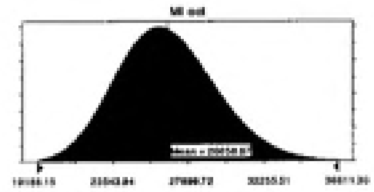
AG_sep (E29)	0.20
Inflow_Sept (C29)	-0.50

Cell:
D30

Assumption: MI oct

Lognormal distribution with parameters:

Mean	26658.87
Standard Dev.	2878.90



Selected range is from 0.00 to +Infinity

Correlated with:

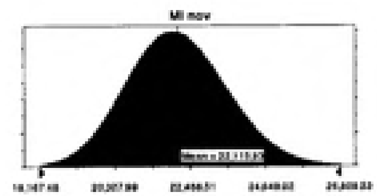
AG_oct (E30)	0.10
Inflow_Oct (C30)	-0.40

Cell:
D31

Assumption: MI nov

Lognormal distribution with parameters:

Mean	22,115.93
Standard Dev.	1,435.82



Selected range is from 0.00 to +Infinity

Correlated with:

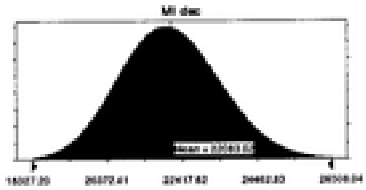
Inflow_Nov (C31)	-0.27
AG_nov (E31)	0.30

Assumption: MI dec

Cell: D32

Lognormal distribution with parameters:

Mean	22083.02
Standard Dev.	1359.62



Selected range is from 0.00 to +Infinity

Correlated with:

AG_dec (E32)	0.40
Inflow_Dec (C32)	-0.25

Appendix B
Water Market Simulation Programs

B.1) Optimal Portfolio
B.2) Rights, Annual Leases, and Options Market

B.1) Optimizing Water Acquisition on a "Liquid" EA Water Market

```
% Modeling the Edwards Aquifer Water Market using Matlab
% Finding the Optimal Amount of Rights to lease, option, buy
% Minimizing Cost of Water Aquisition s.t. a Reliability Constraint

% Percent symbols indicate a comment

clear variables
F_X=0;
F_AG=0;
F_AGuse=0;
F_Muse=0;
addpath('C:\Documents and Settings\sdurbin\My Documents\edaquifer\matlabtools\mcmc')

% List Initial conditions and given information:
e=[-0.8 -0.8 -0.3 -0.3 -0.3 -0.3 -0.3 -0.3 -0.3 -0.8 -0.8 -0.8];     % Agr. Elasticities
AGIRPo=247000;                                                        % Agr. IRPs
MIRPo=226000;                                                         % Municipal IRPs
P0 = 35;                                                              % Pumping Costs

% Percentage of water used in each month
M_per=[7 6.6 7.3 7.9 8.6 9.3 11 11.1 8.8 8.4 7.1 7];
AG_per=[5.76 5.76 5.76 12.19 18.3 18.3 13.14 10.22 5.84 1.58 1.58 1.58];

% We are assuming the rights bought by the municipality get distributed throughout the year
% based on historic usage. However to make the # of monthly failures in each month unbiased,
% we will allot more water to January and less to December so that the # of monthly failures are approximately
% the same for each month of the year.  This also prevents a bias toward annual leases rather than rights.

M_allocate=[11 6.6 7.3 7.9 8.6 9.3 11 11.1 8.8 8.4 7.1 3];

% Calculating constant in the Cobb-Douglas Function
a=AGIRPo/(P0^e(1))

%*******************Change these parameters when running simulation with new January Well Level**************
HSTART=670
XP=49;
OpP=20;
CP=200;          % Choke Price
%****************************************************************************************************
XM=6;     %Exercise Month
%****************************************************************************************************

format short g;

%Monthly log normal demand distributions and correlations.
%Ag demand is in the n loop because it is a function of the decision variables.

Mmean=[9.98877 9.91462 10.0164 10.0885 10.1856 10.2639 10.4078 10.4318 10.20666 10.18508 10.00195 10.00067];
Imean=[10.68 10.77 10.89 10.89 11.35 11.42 10.91 10.64 10.97 11.05 10.71 10.75];
MDmean=0.875*exp(Mmean);
error=[-0.841 -1.8463 -2.356 0.061 1.423 -1.244 -0.267 1.812 2.964 1.883 -0.585 -1.004];
M_A_I=load('dataforcovar3.txt');            % Natural Log Matrix of municipal + industrial use,
```

```
                                        % annual agricultural use, and inflows for 1970-1998
sigma=cov(M_A_I);                       % Covariance Matrix of logged values

% 34,000 AF of rights are bought before the year starts
Buy=34000;
EA_Buy=82000;               % To Reduce Permits to 450,000 AF
EA_Buy2=50000;              % To Reduce Permits to 400,000 AF
EA_Price=22.95;             % Price when Agr. Rights reduced from 247 taf to 165 taf

AGIRP1=AGIRPo-EA_Buy-Buy;
BuyP=(AGIRP1/a)^(1/e(1))-P0;                    % Amortized estimate of Water Right Price
MIRP=MIRPo;

% The following are the combinations of Annual Leases and Options that will be tried in the model
xx=[0:2000:10000 12000:2000:16000];
yy=[0:2500:10000];
[aa,bb]=meshgrid(xx,yy);
y=1;
x=0;
z=0;
s=size(aa,1)*size(aa,2);
while z<s
   z=z+1;
   x=x+1;
   if x==size(aa,1)+1
      y=y+1;
      x=1;
   end
combos(z,1:2)=[aa(x,y) bb(x,y)];
end

z=1
while z<size(combos,1)+1
if combos(z,1)+combos(z,2)>40000
   combos(z,:)=[];
elseif combos(z,1)+combos(z,2)<0
   combos(z,:)=[];
else
  z=z+1;
end
end
size(combos,1);

%******************************** Start of (run) LOOP **********************************
run=0;
while run<size(combos,1)
   run=run+1;

% Selecting the amount of annual leases and options from the combos defined above
AL=combos(run,1);
Op=combos(run,2);
AGIRP=AGIRP1-AL;


% Estimated agricultural demand parameters, mu and sigma
if AGIRP>=200000
```

```
    ADmean= log(0.6*AGIRP);
 elseif AGIRP>100000
    ADmean=log(0.7*AGIRP);
 else
    ADmean=log(0.8*AGIRP);
 end

 %Updating Agricultural means and standard deviations based on amount of IRPs sold
 ADyrmean=exp(ADmean);
 Amean=AG_per/100*ADyrmean;
 PerSD=5.4*10^-6*(AGIRP/1000)^2;
 AgSD=PerSD*ADyrmean;
 sig=(-2*ADmean+log(1/2*exp(2*ADmean)+1/2*(exp(2*ADmean)^2+4*AgSD^2*exp(2*ADmean))^(1/2)))^(1/2);
 ad=M_A_I(1:29,13);
 ad=(ad-mean(ad))/std(ad)*sig+ADmean;
 M_A_I(1:29,13)=ad;

 mu=[Mmean ADmean Imean]';
 sigma=cov(M_A_I);

 % Select the number of "runs" for each decision variable combination
 runs=500;
 n=0;
 %**************************************** Start of (n)  LOOP ****************************************
 while n<runs
 n=n+1
 run

 H=[HSTART 0 0 0 0 0 0 0 0 0 0 0 0];
 L=[0 0 0 0 0 0 0 0 0 0 0 0 0];
 LP=[0 0 0 0 0 0 0 0 0 0 0 0 0];
 X=[0 0 0 0 0 0 0 0 0 0 0 0 0];
 alpha=[a 0 0 0 0 0 0 0 0 0 0 0 0];
 AgPump=[0 0 0 0 0 0 0 0 0 0 0 0 0];
 IRP=[0 0 0 0 0 0 0 0 0 0 0 0 0];
 XD=0;

 % Multivariate Model with Normal Random Numbers
 % The normal distributions are the log of the agr, M/I, and Inflow distributions
 % Sigma is the covariance matrix calculated from 30 years of inflow and outflow data
 % Municipal Demand used for covariance matrix was adjusted to represent current usage
 % Agricultural Demand used for covariance matrix is adjusted based on sales, i.e.- "AL" and "Buy"

 Y=mvnormrnd(mu,sigma,1);
 Ag_D=exp(Y(1,13)).*AG_per/100;
 sum(Ag_D);
 MI_D=exp(Y(1,1:12));
 ID=exp(Y(1,14:25));
 MD=0.875*MI_D;

 i=0;
 while i<12
 % Determine Monthly Permit Amount Based on Well Level
 % With New Cutback Rules
 i=i+1;
    if H(i)<=627
```

```
   IRP(i)=MIRP*M_per(i)*0.70/100;
   elseif H(i)<=630
   IRP(i)=MIRP*M_per(i)*0.80/100;
   elseif H(i)<=640
   IRP(i)=MIRP*M_per(i)*0.85/100;
   elseif H(i)<=650
   IRP(i)=MIRP*M_per(i)*0.90/100;
   else
   IRP(i)=MIRP*M_per(i)/100;
   %IRP(i)=MIRP+sum(L(1:i-1))+XD-sum(MD(1:i-1));
   end

% ****************** Start of Exercise Loop ************************************************************
% If i=6, then we must determine how many options to exercise
% Need J17 June and alpha June, then go into this loop to decide how much to exercise
% Means used to get expected J17 levels and shortfalls

if i==XM
Shortfall=[0 0 0 0 0 0 0 0 0 0 0 0];
E_LP=[0 0 0 0 0 0 0 0 0 0 0 0];
E_H=H;
E_a=alpha;
E_AgPump=AgPump;
for j=XM:1:11;
E_H(j+1)=144.5 + 0.796*E_H(j) + 0.000026*exp(Imean(j))-0.00022*(Amean(j))-0.00036*exp(Mmean(j))+error(j);
end

E_IRP=IRP;
% Determine Monthly Permit Amount Based on Well Level
for k=XM+1:12
if E_H(k)<=627;
  E_IRP(k)=MIRP*M_per(k)*0.7/100;
elseif E_H(i)<=630;
  E_IRP(k)=MIRP*M_per(k)*0.8/100;
elseif E_H(i)<=640;
  E_IRP(k)=MIRP*M_per(k)*0.85/100;
elseif E_H(i)<=650;
  E_IRP(k)=MIRP*M_per(k)*0.9/100;
else
  E_IRP(k)=MIRP*M_per(k)/100;
  %E_IRP(k)=MIRP+sum(L(1:XM-1))-sum(MD(1:XM-1))-sum(MDmean(XM:k-1));
end
end
E_IRP;
E_F=F;
% Predicting the shortfall in each month from the exercise month to the end of the year
k=XM;
while k<13
  if sum(MDmean(XM:k))+sum(MD(1:XM-1))>(sum(Shortfall(XM:k-
1))+sum(E_IRP(1:k))+Buy*sum(M_allocate(1:k))/100+sum(L(1:XM-1)))
     E_F(n,k)=1;
     if sum(sum(E_F))/((n-1)*12+k)>Fail
        Shortfall(k)=sum(MDmean(XM:k))+sum(MD(1:XM-1))-(sum(Shortfall(XM:k-
1))+Buy*sum(M_allocate(1:k))/100+sum(E_IRP(1:k))+sum(L(1:XM-1)));
        E_F(n,k)=0;
```

```
        elseif sum(MDmean(XM:k))+sum(MD(1:XM-1))-(sum(Shortfall(XM:k-
1))+sum(E_IRP(1:k))+Buy*sum(M_allocate(1:k))/100+sum(L(1:XM-1)))>FL
            Shortfall(k)=sum(MDmean(XM:k))+sum(MD(1:XM-1))-(sum(Shortfall(XM:k-
1))+Buy*sum(M_allocate(1:k))/100+sum(E_IRP(1:k))+sum(L(1:XM-1)))-FL;
        end
    else
        E_F(n,k)=0;
        Shortfall(k)=0;
    end

E_LP(k)=((AGIRP-sum(L(2:XM-1))-sum(E_AgPump(1:k-1))-sum(Shortfall(XM:k)))/E_a(k))^(1/e(k))-P0;


if k>XM
    if E_LP(k)-E_LP(k-1)>20
    E_LP(k)=E_LP(k-1)+20;
    elseif E_LP(k)-E_LP(k-1)<-10
    E_LP(k)=E_LP(k-1)-10;
    else
    E_LP(k)=E_LP(k);
    end
else
    if E_LP(k)-LP(k-1)>20
    E_LP(k)=LP(k-1)+20;
    elseif E_LP(k)-LP(k-1)<-10
    E_LP(k)=LP(k-1)-10;
    else
    E_LP(k)=E_LP(k);
    end
end

if E_LP(k)<5
    E_LP(k)=5;
elseif E_LP(k)>CP
    E_LP(k)=CP;
end

E_AgPump(k)=Amean(k)-Shortfall(k);
if E_AgPump(k)<0
    E_AgPump(k)=0;
end

if k<12
E_a(k+1)=(AGIRP-sum(Amean(1:k)))/((E_LP(k)+P0)^e(k+1));
end

if XP<E_LP(k)
    E_X(k)=Shortfall(k);
else
    E_X(k)=0;
end
k=k+1;
end

XD=sum(E_X);
```

```
if XD>Op
   XD=Op;
end
end
% ************************* End of Exercise Loop ********************************************************

% Use Reliability Constraints to Determine How Much to Spot Lease
Fail=0.01;          % Allowing Failure in Certain Percentage of Months in the Simulation
FL=5000;            % Restricts the Magnitude of Shortfall That is Acceptable


if i==1
   L(i)=AL;
else
if sum(MD(1:i))>sum(L(1:i-1))+sum(X(1:i-1))+Buy*sum(M_allocate(1:i))/100+sum(IRP(1:i))
      F(n,i)=1;
   if sum(sum(F))/((n-1)*12+i)>Fail
        if i<XM
        L(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(IRP(1:i))-Buy*sum(M_allocate(1:i))/100;
        F(n,i)=0;
      else
        X(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(X(1:i-1))-sum(IRP(1:i))-Buy*sum(M_allocate(1:i))/100;
        if sum(X)>XD
           X(i)=XD-sum(X(1:i-1));
        end
        L(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(X(1:i))-sum(IRP(1:i))-Buy*sum(M_allocate(1:i))/100;
        if abs(L(i))<1
           L(i)=0;
        end
        F(n,i)=0;
     end
  elseif sum(MD(1:i))-sum(L(1:i-1))+sum(X(1:i-1))+Buy*sum(M_allocate(1:i))/100+sum(IRP(1:i))>FL
     if i<XM
        L(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(IRP(1:i))-Buy*sum(M_allocate(1:i))/100-FL;
      else
        X(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(X(1:i-1))-sum(IRP(1:i))-Buy*sum(M_allocate(1:i))/100-FL;
        if sum(X)>XD
           X(i)=XD-sum(X(1:i-1));
        end
        L(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(X(1:i))-sum(IRP(1:i))-Buy*sum(M_allocate(1:i))/100-FL;
        if abs(L(i))<1
           L(i)=0;
        end
     end
  end
else
   F(n,i)=0;
end
end

% Lease Price Determined by Location of Agricultural Demand Curve and Supply of Agr. Rights
if i>1
LP(i)=((AGIRP-sum(L(2:i))-sum(X(1:i))-sum(AgPump(1:i-1)))/alpha(i))^(1/e(i))-P0;
else
 LP(i)=((AGIRP)/alpha(i))^(1/e(i))-P0;
end
```

```
% Lease Price Volatility is constrained to a range that is consistent with other water markets
if i>1
if LP(i)-LP(i-1)>20
   LP(i)=LP(i-1)+20;
elseif LP(i)-LP(i-1)<-10
   LP(i)=LP(i-1)-10;
else
   LP(i)=LP(i);
end
end

% Minimum Lease Price=$5/AF, Maximum Price=$200/AF
if LP(i)<5
   LP(i)=5;
elseif LP(i)>CP
   LP(i)=CP;
end

% It is assumed that when agr. users sell on the spot market, their demand is reduced by that much
if i>1
AgPump(i)=Ag_D(i)-L(i)-X(i);
else
AgPump(i)=Ag_D(i);
end

if AgPump(i)<0
   AgPump(i)=0;
end

% Calculating the constant in the Cobb-Douglas function for the next month
if i<12
  alpha(i+1)=(AGIRP-sum(Amean(1:i)))/((LP(i)+P0)^e(i+1));
end

% Calculating the well height at the start of the next month
if i<12
   H(i+1)=144.5 + 0.796*H(i) + 0.000026*ID(i)-0.00022*AgPump(i)-0.00036*MI_D(i)+error(i);
end
end
%*************** End of Annual Loop, i=i+1 back to top of loop***********

% The Annual cost of meeting demand for this simulation run
% The cost of the large purchases ("Buy", "AL") are calculated by trapezoidal estimate
Cost=Buy*.5*(BuyP+EA_Price)+Op*OpP+XP*XD+.5*(LP(1,1)+BuyP)*AL+ sum(L(1,2:12).*LP(1,2:12));

% These variables store values for later analysis
F_X(n,1)=sum(X);
F_L(n,1:12)=L;
F_XD(n,1)=XD;
F_Cost(n,1)=Cost;
F_LP(n,1:12)=LP;
%F_E_LP(n,1:12)=E_LP
F_H(n,1:12)=H;

end
```

```
%****************** END OF (n) LOOP, repeats 500+ for each decision variable combo **********************

F_monthly(run,1:12)=sum(F);
Ave_H(run,1:12)=mean(F_H);
Ave_Leases(run,1:12)=mean(F_L);
Ave_LP(run,1:12)=mean(F_LP);
StDev_LP(run,1:12)=std(F_LP);
T_AL(run,1)=AL;
T_Op(run,1)=Op;
Ave_X(run,1)=mean(sum(F_X,2));
Ave_XD(run,1)=mean(F_XD);
Ave_L(run,1)=mean((sum(F_L,2)));
Ave_cost(run,1)=mean(F_Cost);
SD_cost(run,1)=std(F_Cost);
clear F
end
%********************** End of (run) LOOP, Number of Annual Leases and Options Changed and Loop Repeats***

% Plot of Annual Leases vs Cost
figure(1)
plot(T_AL,Ave_cost,'X')
xlabel('AL (AF)')
ylabel('Cost ($)')
title(['Jan.J17=',num2str(HSTART),', XM=',num2str(XM)])

%Plot of Options vs. Cost
figure(2)
plot(T_Op,Ave_cost,'X')
xlabel('Options (AF)')
ylabel('Cost ($)')
title(['Jan.J17=',num2str(HSTART),', XM=',num2str(XM)])

% Averages for all portfolios, all runs
F_Ave_Leases=mean(Ave_Leases)
F_Ave_H=mean(Ave_H)
F_Ave_LP=mean(Ave_LP)
F_std_LP=mean(StDev_LP)
F_Ave_cost=mean(Ave_cost)
F_std_cost=mean(SD_cost)
Failures=F_monthly./runs;

s=[T_AL T_Op Ave_X Ave_XD Ave_L Ave_cost];
t=[HSTART XM XP F_Ave_LP(XM)]
[g,h]=min(Ave_cost);

% Outputs Lowest Cost Market Portfolio
Opt=['     AL''     Op''     Ave_X''     Ave_XD''     Ave_L''     Ave_cost']
Opt=s(h,:)

% Generates output file of all portfolios and their average cost
save leasegrunt_results.out s -ASCII;


% 3-D plot of Annual leases, Options, and Cost
figure(3)
xx=0:1000:25000;
```

```
yy=0:1000:25000;
[aa,bb]=meshgrid(xx,yy);
cc=griddata(T_AL,T_Op,Ave_cost,aa,bb);
pcolor(aa,bb,cc)
shading interp
colorbar
grid
title(['Jan.J17=',num2str(HSTART),', XM=',num2str(XM),', R=',num2str(Fail)])
xlabel('AL(AF)')
ylabel('Options (AF)')
text(T_AL(h),T_Op(h),'MIN','color',[1 1 1])
```

B.2) Rights, Annual Leases, and Options Market

```
% Modeling the Edwards Aquifer Water Market using Matlab
% Market Alternatives are permanent transfers, annual leases, and options
% Minimizing Cost of Water Aquisition s.t. a Reliability Constraint
% "Buy" and "AL" have been solved for: this model determines the number of
% options to purchase if no spot market is available.
% Model also solves for the number of rights to exercise.
% The failure rate is calculated at the end of the simulation for each portfolio
% The portfolio that minimizes cost while acheiving the desired level of reliability is deemed optimal

clear variables
F_X=0;
F_AG=0;
F_AGuse=0;
F_Muse=0;
addpath('C:\Documents and Settings\sdurbin\My Documents\edaquifer\matlabtools\mcmc')

% List Initial conditions and given information:
% Elasticities
e=[-0.8 -0.8 -0.3 -0.3 -0.3 -0.3 -0.3 -0.3 -0.3 -0.8 -0.8 -0.8];

% Permits issued to Agriculture and Municipalities by the EAA
AGIRPo=247000;
MIRPo=226000;
P0 = 35;                          % Agricultural Pumping Cost

% Percent Usage in Each Month
M_per=[7 6.6 7.3 7.9 8.6 9.3 11 11.1 8.8 8.4 7.1 7];
AG_per=[5.76 5.76 5.76 12.19 18.3 18.3 13.14 10.22 5.84 1.58 1.58 1.58];

% We are assuming the the rights bought by the municipality get distributed throughout the year
% based on historic usage. However to make the # of monthly failures in each month unbiased,
% we will allot more water to January and less to December so that the # of monthly failures are approximately
% the same for each month of the year.  This also prevents a bias toward annual leases rather than rights.
M_allocate=[11 6.6 7.3 7.9 8.6 9.3 11 11.1 8.8 8.4 7.1 3];

a=AGIRPo/(P0^e(1))

%******************Change these parameters when running simulation with new January Well Level**************
HSTART=670
XP=50;
OpP=20;
CP=200;           % Choke Price
%***************************************************************************************************
XM=6;      %Exercise Month
%***************************************************************************************************

format short g;

% Use monthly log normal demand distributions and correlations.
%Ag demand is in the n loop because it is a function of the decision variables.

Mmean=[9.98877 9.91462 10.0164 10.0885 10.1856 10.2639 10.4078 10.4318 10.20666 10.18508 10.00195 10.00067];
Imean=[10.68 10.77 10.89 10.89 11.35 11.42 10.91 10.64 10.97 11.05 10.71 10.75];
MDmean=0.875*exp(Mmean);
```

```
error=[-0.841 -1.8463 -2.356 0.061 1.423 -1.244 -0.267 1.812 2.964 1.883 -0.585 -1.004];
M_A_I=load('dataforcovar3.txt');  % Natural Log Matrix of Municipal+Industrial Use, Annual Agricultural Use, and Inflows
for 1970-1998
sigma=cov(M_A_I);                 % Covariance Matrix of logged values


EA_Buy=82000;               % To Reduce Permits to 450,000 AF
EA_Buy2=50000;              % To Reduce Permits to 400,000 AF
EA_Price=22.95;

% 34,000 AF of rights are bought before the year starts
Buy=34000;
AGIRP1=AGIRPo-EA_Buy-Buy;
BuyP=(AGIRP1/a)^(1/e(1))-P0;
MIRP=MIRPo;

AL=10000;
AGIRP=AGIRP1-AL;


% Estimated agricultural demand parameters, mu and sigma
if AGIRP>=200000
   ADmean= log(0.6*AGIRP);
elseif AGIRP>100000
   ADmean=log(0.7*AGIRP);
else
   ADmean=log(0.8*AGIRP);
end

%Updating Agricultural means and standard deviations based on amount of IRPs sold
ADyrmean=exp(ADmean);
Amean=AG_per/100*ADyrmean;
PerSD=5.4*10^-6*(AGIRP/1000)^2;
AgSD=PerSD*ADyrmean;
sig=(-2*ADmean+log(1/2*exp(2*ADmean)+1/2*(exp(2*ADmean)^2+4*AgSD^2*exp(2*ADmean))^(1/2)))^(1/2);
ad=M_A_I(1:29,13);
ad=(ad-mean(ad))/std(ad)*sig+ADmean;
M_A_I(1:29,13)=ad;
mu=[Mmean ADmean Imean]';
sigma=cov(M_A_I);

% The following are the combinations of Options and the amount of Options to be exercised
% The amount of options to exercise is a function of the expected shortfall calculated in the simulation
% The values in the vector "yy" are amounts above the expected shortfall that will be exercised
% The variable name for the amount of options above expected to exercise is "Per_x"

xx=[17000 18000 21000 23000 26000];
yy=[7000:1000:10000 12000:2000:20000];
[aa,bb]=meshgrid(xx,yy);
y=1;
x=0;
z=0;
s=size(aa,1)*size(aa,2);
while z<s
   z=z+1;
   x=x+1;
```

```
   if x==size(aa,1)+1
      y=y+1;
      x=1;
   end
 combos(z,1:2)=[aa(x,y) bb(x,y)];
 end

 z=1
 while z<size(combos,1)+1
 if combos(z,1)+combos(z,2)>50000
    combos(z,:)=[];
 elseif combos(z,1)+combos(z,2)<0
    combos(z,:)=[];
 else
   z=z+1;
 end
 end
 size(combos,1)

 %******************************* Start of "Run" LOOP **********************************
 run=0;
 while run<size(combos,1)
    run=run+1

 % Choosing the combination of options and the amount to exercise
 Op=combos(run,1);
 Per_X=combos(run,2);


 runs=500;
 n=0;
 %****************************************** Start of "n" LOOP   ******************************************
 while n<runs
 n=n+1
 run

 H=[HSTART 0 0 0 0 0 0 0 0 0 0 0];
 L=[0 0 0 0 0 0 0 0 0 0 0 0];
 LP=[0 0 0 0 0 0 0 0 0 0 0 0];
 X=[0 0 0 0 0 0 0 0 0 0 0 0];
 alpha=[a 0 0 0 0 0 0 0 0 0 0 0];
 AgPump=[0 0 0 0 0 0 0 0 0 0 0 0];
 IRP=[0 0 0 0 0 0 0 0 0 0 0 0];
 XD=0;

 Y=mvnormrnd(mu,sigma,1);
 Ag_D=exp(Y(1,13)).*AG_per/100;
 sum(Ag_D);
 MI_D=exp(Y(1,1:12));
 ID=exp(Y(1,14:25));
 MD=0.875*MI_D;

 i=0;
 while i<12
 % Determine Monthly Permit Amount Based on Well Level
 i=i+1;
```

```
   if H(i)<=630
   IRP(i)=MIRP*M_per(i)*0.85/100;
   elseif H(i)<=640
   IRP(i)=MIRP*M_per(i)*0.9/100;
   elseif H(i)<=650
   IRP(i)=MIRP*M_per(i)*0.95/100;
   else
   IRP(i)=MIRP*M_per(i)/100;
   %IRP(i)=MIRP+sum(L(1:i-1))+XD-sum(MD(1:i-1));
   end

% ******************* Start of Exercise Loop ************************************************************
% If i=6, then we must determine how many options to exercise
% Need J17 June and alpha June, then go into this loop to decide how much to exercise
% Means used to get expected J17 levels and shortfalls

if i==XM
Shortfall=0;
E_LP=[0 0 0 0 0 0 0 0 0 0 0 0 0];
E_H=H;
E_a=alpha;
E_AgPump=AgPump;
for j=XM:1:11;
E_H(j+1)=144.5 + 0.796*E_H(j) + 0.000026*exp(Imean(j))-0.00022*(Amean(j))-0.00036*exp(Mmean(j))+error(j);
end

E_IRP=IRP;
% Determine Monthly Permit Amount Based on Well Level
for k=XM+1:12
if E_H(k)<=630;
   E_IRP(k)=MIRP*M_per(k)*0.85/100;
elseif E_H(i)<=640;
   E_IRP(k)=MIRP*M_per(k)*0.9/100;
elseif E_H(i)<=650;
   E_IRP(k)=MIRP*M_per(k)*0.95/100;
else
   E_IRP(k)=MIRP*M_per(k)/100;
   %E_IRP(k)=MIRP+sum(L(1:XM-1))-sum(MD(1:XM-1))-sum(MDmean(XM:k-1));
end
end
E_IRP;

% Predicting the shortfall in each month from the exercise month to the end of the year

   if sum(MDmean(XM:12))+sum(MD(1:XM-1))>sum(E_IRP(1:12))+Buy+sum(L(1:XM-1))
        Shortfall=sum(MDmean(XM:12))+sum(MD(1:XM-1))-(Buy+sum(E_IRP(1:12))+sum(L(1:XM-1)));
   else
      Shortfall=0;
   end


XD=Per_X+Shortfall;

if XD>Op
```

```
   XD=Op;
end
end
% ************************* End of Exercise Loop *********************************************************

% Because spot market leases are not available on this market, we can't make up for shortfalls
% before the exercise month. Therefore, the bought rights are not distributed throughout
% the year as they are in the liquid market simulations. This makes shortfalls occur after June,
% and options can be exercised to meet reliablity constraints when those shortfalls occur.
% Whenever there is a shortfall, options that have been exercised are used to meet the demand
% If there are no rights, leases, or exercised options remaining to use, then municipalities fail to meet demand
% The failure rate is calculated at the end of the 500+ runs for each portfolio
% The portfolio that meets the desired level of reliability at the minimum cost is the optimal portfolio on this market

if i==1
   L(i)=AL;
else
if sum(MD(1:i))>sum(L(1:i-1))+sum(X(1:i-1))+Buy+sum(IRP(1:i))
       F(n,i)=1;
       if i>=XM
          X(i)=sum(MD(1:i))-sum(L(1:i-1))-sum(X(1:i-1))-sum(IRP(1:i))-Buy;
          if sum(X)>XD
             X(i)=XD-sum(X(1:i-1));
          else
             F(n,i)=0;
          end
      end

else
   F(n,i)=0;
end
end

if i==1
 LP(i)=((AGIRP)/alpha(i))^(1/e(i))-P0;
end

if i>1
AgPump(i)=Ag_D(i)-L(i)-X(i);
else
AgPump(i)=Ag_D(i);
end

if AgPump(i)<0
   AgPump(i)=0;
end

if i<12
  alpha(i+1)=(AGIRP-sum(Amean(1:i)))/((LP(i)+P0)^e(i+1));
end

if i<12
   H(i+1)=144.5 + 0.796*H(i) + 0.000026*ID(i)-0.00022*AgPump(i)-0.00036*MI_D(i)+error(i);
end
end
```

```
Cost=Buy*.5*(BuyP+EA_Price)+Op*OpP+XP*XD+.5*(LP(1,1)+BuyP)*AL+ sum(L(1,2:12).*LP(1,2:12));

F_X(n,1)=sum(X);
F_XD(n,1)=XD;
F_Cost(n,1)=Cost;
F_H(n,1:12)=H;
%F_ID(n,1)=sum(ID);
%F_MD(n,1)=sum(MD);
%F_Short(n,1)=sum(Shortfall);
%F_Leases(n,1)=sum(L(XM:12),2);
%Diff(n,1)=F_MD(n,1)-F_L(n,1)-Buy-MIRP;
end
%****************** END OF (n) LOOP ***************************************************************

Ave_H(run,1:12)=mean(F_H);
F_totals(run,1)=sum(sum(F))/(n*12);
F_monthly(run,1:12)=sum(F);
T_Per_X(run,1)=Per_X;
T_Op(run,1)=Op;
Ave_X(run,1)=mean(sum(F_X,2));
Ave_XD(run,1)=mean(F_XD);
Ave_cost(run,1)=mean(F_Cost);
SD_cost(run,1)=std(F_Cost);
clear F
end
%********************** End of Options & Amount to Exercise (run) Loop ************************************
figure(1)
plot(T_Per_X,F_totals,'X')
xlabel('Amount above Expected)')
ylabel('Failure %')
title(['Jan.J17=',num2str(HSTART),', XM=',num2str(XM)])

figure(2)
plot(T_Op,Ave_cost,'X')
xlabel('Options (AF)')
ylabel('Cost ($)')
title(['Jan.J17=',num2str(HSTART),', XM=',num2str(XM)])


F_Ave_H=mean(Ave_H)
F_Ave_cost=mean(Ave_cost)
F_std_cost=mean(SD_cost)


s=[T_Per_X T_Op Ave_X Ave_XD F_totals Ave_cost]
t=[HSTART XM XP]
[g,h]=min(Ave_cost);
Opt=['   Percent' '     Op' '      Ave_X' '      Ave_XD' '      Ave_L' '      Ave_cost']
Opt=s(h,:)
save option_results.out s -ASCII;

figure(3)
xx=0:1000:40000;
yy=0:1000:20000;
[aa,bb]=meshgrid(xx,yy);
```

```
cc=griddata(T_Op,T_Per_X,Ave_cost,aa,bb);
pcolor(aa,bb,cc)
shading interp
colorbar
grid
title(['Jan.J17=',num2str(HSTART),', XM=',num2str(XM),', R=',num2str(Fail)])
xlabel('Options (AF)')
ylabel('Amount over Expected(AF)')
text(T_Per_X(h),T_Op(h),'MIN','color',[1 1 1])
```

Appendix C
Non-Liquid Market Simulations

Appendix C: Non-Liquid Market Simulations

A model developed using the *Excel* simulation package called *Crystal Ball (CB)* was used to simulate the less complex market types. Namely, a market that used only permanent transfers and one that used permanent transfers and annual leases were simulated in *CB*. Spot market leases were utilized in the *Matlab* simulations to meet the reliability constraints. However, the more simple markets simulated in *CB* did not use spot leases, and therefore, the reliability level of these markets had to be calculated ex-post. The speed of the *CB* simulations made it desirable to use. All the data and the recharge and demand probability distributions were the same as in the *Matlab* simulations.

The following procedure was used to find the number of rights necessary to meet 99% reliability:

First, the January J17 well height was replaced by its probability distribution. Because permanent transfers are the only alternative on this market, the starting well height is not known. Therefore, the municipality has to prepare for all possible starting well heights in order to meet 99% reliability. Next, the amount of rights expected to provide 99% reliability was inputted into the simulation model. The Monte Carlo simulation ran 1000 trials at the given number of rights, tallying the monthly failures as they occurred. At the end of the simulation, the results were extracted and the number of failures calculated. For 99% reliability, there has to be 120 or fewer failures. If the number was greater than this, the number of rights would be increased and the program rerun until the 99% reliability level was reached.

Some examples of trial runs are shown in Table C.1. There are 1000 simulation runs per trial, and the January well level is sampled from its distribution at the start of each simulation run. Rights were distributed throughout the year based primarily on historic percent use in each month; however, additional rights were taken from December and allocated to January to reduce the number of minor failures that otherwise would occur at the start of the year.

Table C.1: Example Results from "Rights Only" Market

Trial	Rights	Monthly Failures	Failure %
1	72000	202	1.68%
2	72500	169	1.41%
3	72500	171	1.43%
4	72700	130	1.08%
5	72800	121	1.01%
6	72800	204	1.70%
7	72800	167	1.39%
8	72800	168	1.40%
9	72900	178	1.48%
10	73000	106	0.88%
11	73000	148	1.23%
12	73000	151	1.26%
13	73000	121	1.01%
14	73000	100	0.83%
15	73200	113	0.94%

From these results, it appears that the lowest number of rights that consistently meets 99% reliability is 73,000 AF.

For the rights and annual leases market type, a similar process was followed. However, with annual leases available, the starting well level in January is known. Therefore, the average January starting well height of 670' was used to find the number of rights and annual leases needed to meet 99% reliability. Example results from some trials are shown below. There are 1000 simulation runs per trial. In these simulations, the number of rights was set at 34,000 AF.

Table C.2: Example Results from "Rights & Annual Leases" Market

Trial	AL	Monthly Failures	Failure %
1	35000	125	1.04%
2	34800	92	0.77%
3	34800	115	0.96%
4	34700	119	0.99%
5	34700	104	0.87%
6	34600	113	0.94%
7	34600	101	0.84%
8	34500	102	0.85%
9	34400	103	0.86%
10	34000	156	1.30%

11	34200	108	0.90%
12	34100	83	0.69%
13	34100	104	0.87%
14	34000	92	0.77%
15	34000	124	1.03%

As evident from the two tables presented above, the failure percentage varied in each trial run, even if the number of purchases remained the same. Thus, there is a range of rights and annual leases in which 99% reliability is likely to be meet. The number of annual leases that meet 99% is approximately 34,500 AF, plus or minus about 400 AF.

Appendix D
Example Results from Market Simulations

D.1) Solving for the Optimal # of Rights
D.2) Rights, Annual Leases, and Options Market: Simulation Results
D.3) Liquid Market Simulation Results

D.1) Solving for the Optimal Number of Rights to Buy

Because rights are the only market instrument bought in perpetuity and because the simulations are one year in duration, a separate decision for finding the optimal number of rights was required. To solve for the optimal number of rights, the simulation model was run at the historical average starting January well height of 670'. This is the expected value of the January well height, and therefore, on average, this is the annual situation that the municipalities will face. The simulation model solves for two decision variables at a time, but there are three decision variables in the liquid market optimization- rights, annual leases, and options. To solve for the third decision variable (rights), a level of rights was input manually into the model and the simulation was run to find the number of options and annual leases that minimized cost for that number of rights. This process was repeated, changing the number of rights each time, until the number of rights that minimized cost began to converge to a value. Through this process, it was determined that 34,000 AF is the optimum level of rights to buy.

To support this conclusion, the simulation model was also run at a very high starting well level (685') at which it was assumed that annual leases would be negligible. In this case, the simulation model solves for the combination of rights and options that minimizes cost, while setting annual leases at zero. The simulation model tested hundreds of pairs of options and permanent transfer amounts to find the combination that resulted in the lowest cost of meeting 99% reliability. The results of this simulation run are presented in Figure D.1.

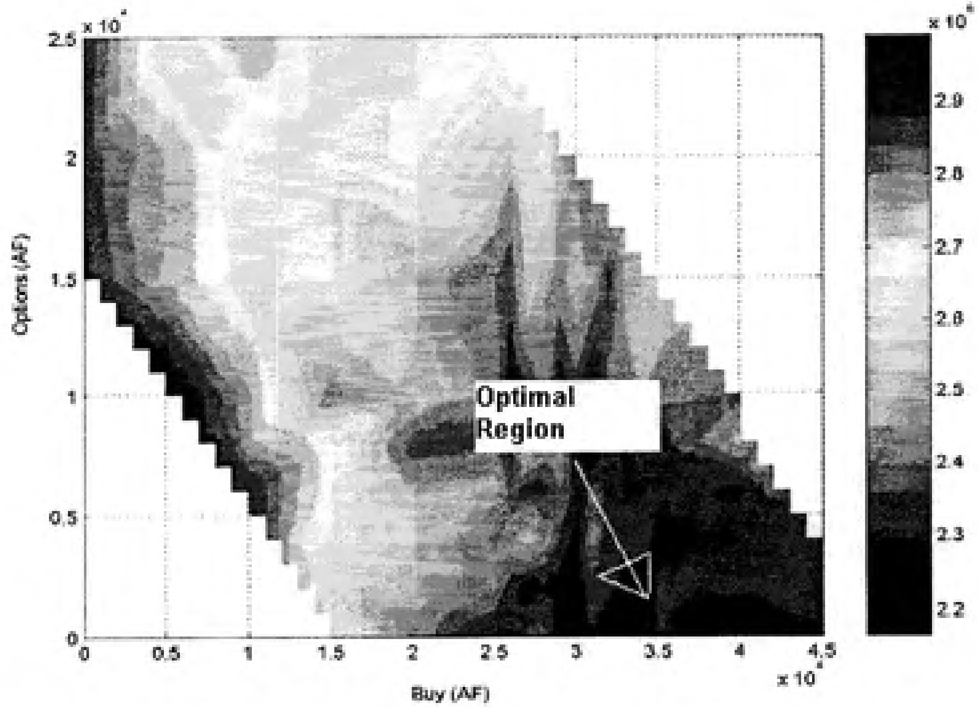


Figure D.1: Finding the Optimal Number of Rights to Buy

The color bar to the right of Figure D.1 indicates the cost ($/yr) of meeting demand for the particular combination of options and rights. The darker colors represent the lowest costs, i.e. - the optimal region. The results of the simulation with J17 January at 685' indicate that the optimal number of rights to purchase is 34,000 AF. This value is the same as the amount found when ran at 670'. Therefore, 34,000 AF was used as the optimum level of rights to buy in the rest of the simulation runs.

D.2) Options Market: Simulation Results

The Options Market consists of 3 transfer types: rights, annual leases, and options. The optimal number of rights to buy is set at 34,000 AF. Numerous combinations of options and annual leases are tried in the simulations, and the combination that gives the minimum cost while meeting 99% monthly reliability is selected as the optimal portfolio. Because there are no spot leases in this market to use as a slack variable, the reliability constraint cannot be directly enforced in the model. Rather, the failure rate for each portfolio is calculated at the end of the simulation and compared to the desired reliability level.

The exercise decision in the model is based on predicting the expected shortfall from June-December. The model predicts the expected shortfall, and exercises a certain number of options above the expected amount in order to meet 99% reliability. The number of options to exercise in excess of the expected shortfall is treated as a decision variable, along with the number of options and annual leases to buy. The simulation program was run several different times, in order to see if the optimal portfolio found from the simulation would change. Table D.1 displays some example results from simulations with the starting well level at 670'. The rows represent the portfolio that minimized cost at 99% reliability for 10 different runs of the program.

Table D.1: Optimal Portfolios From 10 Different Runs of the Model

Trial	Above (AF)	Option (AF)	X (AF)	XD (AF)	AL (AF)	Total (AF)	Failure	Cost ($/yr)
1	16000	23000	3613	17186	14000	65186	0.93%	3086670
2	16000	19500	2912	16584	15000	65584	0.93%	3042545
3	16000	26000	4979	18274	12000	64274	0.98%	3092383
4	16000	18000	3249	16400	15000	65400	1.03%	3003550
5	16000	18000	3498	16409	15000	65409	1.08%	3003978
6	16000	19500	3512	16616	15000	65616	0.98%	3044102
7	16000	19000	3631	16497	15000	65497	1.02%	3028313
8	16000	20000	3606	16636	15000	65636	1.12%	3055116
9	16500	19500	3588	17059	15000	66059	1.05%	3065817
10	15500	20000	3243	16234	15000	65234	1.02%	3035425
Average	16000	20250	3583	16790	14600	65390	1.02%	3045790
St. Dev.	236	2452	542	598	966	462	0.001	30348

where,

Above is the number of options exercised in excess of the expected shortfall quantity

Option is the number of options bought at the start of year

XD is the number of options that are exercised

X is the average number of exercised options that get used

AL is the number of annual leases bought at the start of the year

Total is the total number of purchases (including rights)

Failure is the percent of the time that the municipalities fail to meet monthly demand

Cost is the average cost of meeting demand for that portfolio

From these 10 different runs of the simulation program, the average optimal portfolio is 34,000 AF of rights, 20250 AF of options, and 14600 AF of annual leases. In order to meet 99% reliability for this portfolio, we have to exercise 16,000 AF more options that we expect to use. The average annual cost is $3 million, and the standard deviation in the average cost of the optimal portfolios is $30,000.

D.3) Liquid Market Simulation Results

The liquid market simulations were run several different times to determine the accuracy and precision of the results. Table D.2 displays the optimal portfolio found in ten different runs of the program with a January well height of 670' and a monthly reliability of 99%.

Table D.2: Example Optimal Portfolios Found Through Simulation

	Purchases (AF)					
Trial	Annual Leases	Options	Exercised Options	Spot Leases	Total	Cost (Million $)
1	8000	2500	888	6037	48925	2.17
2	8000	2500	960	6699	49659	2.26
3	10000	0	0	6047	50047	2.22
4	8000	2500	892	6102	48994	2.18
5	8000	1000	379	7299	49678	2.20
6	6000	2000	955	7380	48335	2.21
7	8000	4000	1327	5644	48971	2.19
8	8000	0	0	7138	49138	2.19
9	8000	0	0	7358	49358	2.19
10	8000	1000	379	6835	49214	2.19
Average	8000	1550	578	6654	49232	2.20
St.Dev	943	1363	486	648	482	0.026

In these ten runs, the optimal number of annual leases averages 8000 AF/yr with a standard deviation of 900. The optimal number of options shows a high standard deviation, varying from 0 to 4000 AF/yr. These values indicate the optimal range of options and annual leases to buy when the starting well level is at 670'.The total number of purchases and the average cost show little variation between optimal portfolios, with standard deviations of around 1% of their means. More example results for different well levels on the following page.

D.3: Optimal Portfolio Results: Jan. J17 = 650'

	Purchases (AF)					
Trial	Annual Leases	Options	Exercised Options	Spot Leases	Total	Cost (Million $)
1	8000	0	0	8167	50167	2.29
2	10000	0	0	7230	51230	2.33
3	10000	0	0	6779	50779	2.27
4	10000	0	0	6893	50893	2.30
5	8000	4000	1462	6670	50132	2.29
6	8000	2000	825	7262	50087	2.32
7	10000	3000	969	6168	51137	2.32
8	6000	1000	474	9041	49515	2.32
9	8000	3000	1210	7169	50379	2.30
10	6000	3000	1276	8223	49499	2.29
Average	8400	1600	622	7360	50382	2.30
St.Dev	1578	1578	597	865	618	0.018

Table D.4: Optimal Portfolio Results: Jan. J17 = 685'

	Purchases (AF)					
Trial	Annual Leases	Options	Exercised Options	Spot Leases	Total	Cost (Million $)
1	6000	0	0	8101	48101	2.16
2	6000	0	0	8134	48134	2.14
3	8000	0	0	7207	49207	2.20
4	4000	1000	507	9217	47724	2.19
5	4000	1000	505	9359	47865	2.16
6	6000	2000	879	7634	48514	2.19
7	6000	0	0	8516	48516	2.18
8	8000	0	0	6839	48839	2.15
9	10000	1000	329	5480	49809	2.19
10	6000	1000	432	7516	47948	2.13
Average	6400	600	265	7800	48466	2.17
St.Dev	1838	699	312	1151	660	0.03

Appendix E: Economic Demand Functions

The mathematical functions that describe the price-quantity relationship can be of several forms, however the typical function takes the form of a downward sloping curve that is concave with respect to the origin. The price, P, is plotted on the y-axis, and the quantity demanded, P, is on the x-axis. However, the function used to form the demand curve, the Cobb-Douglas equation, is normally written as shown below.

$$Q = a * P^{\varepsilon} \qquad \text{Equation D.1}$$

Where: Q = quantity
P = price

Cobb-Douglas is the most common functional form used to fit water demand data. It has also been shown to be at least as effective at explaining the price-quantity relationship as linear, translog, or Fourier models (Griffin and Chang 1991). The main advantage of the Cobb-Douglas form is that the elasticity, ε in Equation 2.1, is a constant. Price elasticity of demand is defined as the percentage change in quantity demanded with a one percent change in price (Equation 2.2).

$$\varepsilon = \frac{(\Delta q / q)}{(\Delta P / P)} \qquad \text{Equation D.2}$$

Elasticities are negative for downward sloping demands, and the magnitude is used to categorize demand for the good as either elastic or inelastic (See Table 2.3). For example, if a good is price elastic, a one percent change in price with cause a greater than one percent decrease in the quantity of the good demanded. Inelastic goods are less affected by price increases, with a one percent price rise corresponding to a decline in demand of less than one percent. Table D.1 briefly summarizes the ranges of price elasticity of demand.

Table D.1 Ranges of Price Elasticity of Demand

Elasticity Value	Type of Economic Behavior
$\varepsilon < -1$	Elastic
$\varepsilon = -1$	Unitary Elastic
$0 > \varepsilon > -1$	Inelastic

Appendix F: Modeling the J17 Well

Figure F.1 compares the historic J17 well levels versus those found by using Equation 3.1. In Figure 3.1, January well level is used to predict only one year ahead. If, instead, the January well level is used to predict long into the future, the error between predicted well height and actual well height will grow steadily over time. Figure F.1 compares the accuracy of a five-year prediction versus one in which the January well height of each year is known.

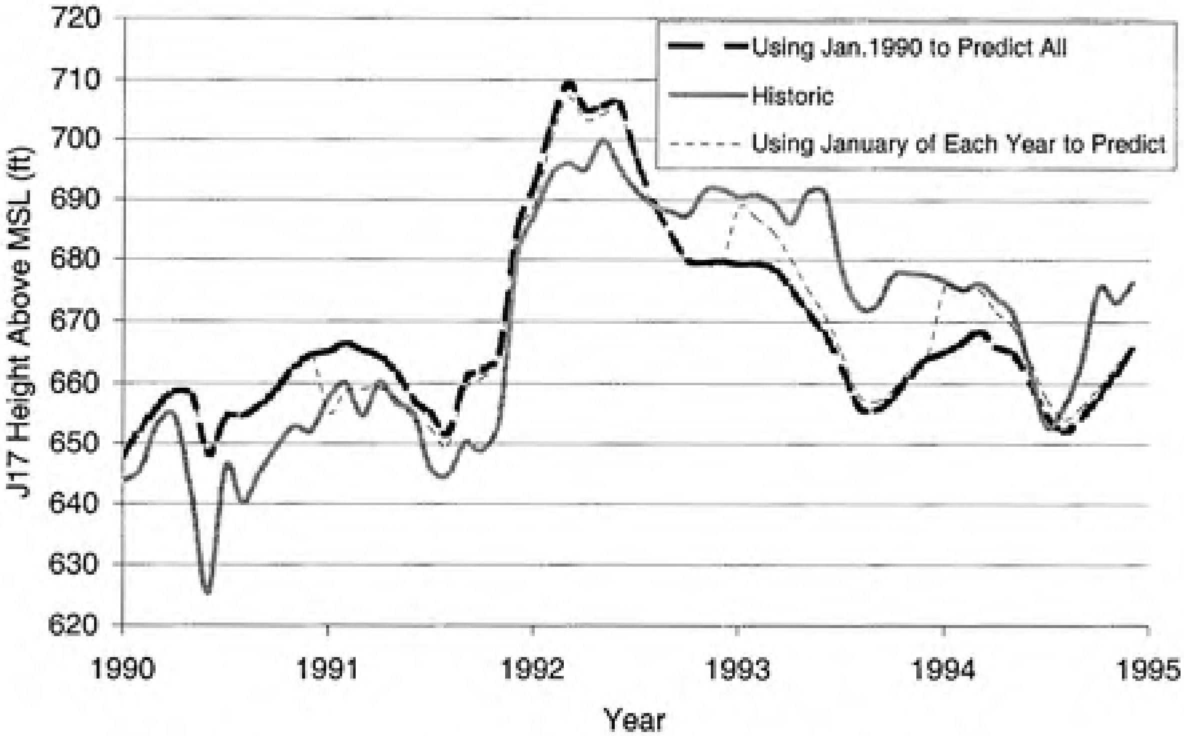


Figure F.1: Predicted vs. Historic Well Heights

Because we are using a single-year simulation model, the problem of propagating errors throughout the J17 predictions was not considered a serious issue and was neglected in the analyses.